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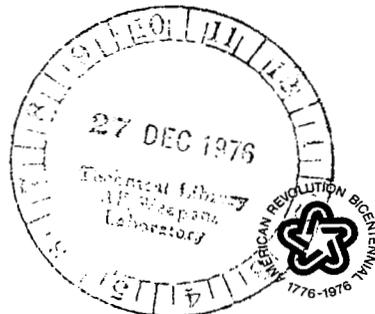
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**SEDIMENT MEASUREMENT IN
ESTUARINE AND COASTAL AREAS**

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Prepared by
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16. Abstract The discussion begins with a survey of uses of estuarine and coastal areas. Problems associated with these uses are discussed, and data needs for intelligent management of these valuable areas are outlined. Suspended sediment measurements are seen to be one of the greatest needs. To help understand the complexity of the problem, a brief discussion of sediment mechanics is given, including sediment sources, characteristics, and transport. The impact of sediment mechanics on its direct measurement (sampling and analysis) is indicated, along with recommendations for directly obtaining representative data. Indirect measurement of suspended sediment by remote sensors is discussed both theoretically and in the light of some recent experiences. The need for an integrated, multidisciplinary program to solve the problem of quantitatively measuring suspended sediment with remote sensors is stressed, and several important considerations of such a program and benefits to be derived therefrom are briefly addressed. It is recommended that the present, very preliminary look be expanded into a full-blown program plan for developing a timely and affordable solution to the problem.			
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FOREWORD

Doubtless some readers may feel that this expository goes into too much detail in some areas, while only slightly touching on others that are of equal importance, and this may well be true. The writer's intention was not to provide a uniform treatise on the subject, but to touch upon some of the major issues and highlight a few that are felt to be critical to the problem at hand; namely, the cost-effective measurement of suspended sediment in estuarine and coastal areas. The writing was prompted by the very complex nature of the problem and seeming inconsistencies in the results being obtained by current researchers. This report is not meant to be critical of any particular work, but hopefully, does point out the urgent need for a unified, multidisciplinary program if progress is to keep abreast of the stresses being placed on the nation's estuarine and coastal zones.

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"The highest object at which the natural sciences are constrained to aim, but which they never reach, is the determination of the forces which are present in nature, and of the state of matter at any given moment - in one word, the reduction of all the phenomena of nature to mechanics."

Gustav Robert Kirchoff (1865)

SECTION I INTRODUCTION

Water is a necessity for life. It is a coolant, cleanser, and diluent; a source of food, energy, mineral, and chemical resources; a sustainer of shipping and navigation; and a source of tranquil, aesthetic, and recreational enjoyment. It is also the ultimate recipient of the residual, nonreclaimable fraction of the output of man's activities, acting as a defiled purveyor of civilization's wastes, a transporter of disease, and a refuge for biological pests and nuisances. Water means different things to different people, and its definition and perceived value depend to a great extent upon the needs and experiences of the individual. The waters of interest here are those of the fluvial, estuarine, and coastal zone; that area where land, freshwater, and the sea are co-mingled into a delicately balanced ecosphere that is extremely vulnerable to human influence.

Although his primordial life forms may have come from the sea, man himself is basically a land animal, but his historical development has been closely linked with the estuarine and coastal zone areas that are of present interest. They lie in proximity to man's terrestrial habitat and can be subjected to more intense levels of use than any other water area. Seven of the world's ten largest metropolitan areas are within this zone. It contains over one-third of the population of the United States, and their life styles, if not their very lives, are dependent upon these waters.

USES OF ESTUARINE AND COASTAL AREAS

The estuarine and coastal zone is used in a myriad of ways, some of which parallel those of inland areas and others of which arise because of unique properties of the area itself. With attention focused more on the latter category, some of the major fundamental uses are:

1. Commercial Marine Transportation - including ports, channels, harbors, shipping lanes, navigation aids.
2. Food Production - including agriculture, commercial fishing, shellfish harvesting.
3. Mineral Resource Recovery - especially sand and gravel.
4. Offshore Development - including oil and gas wells, floating ports, nuclear power plants.
5. Preserves of Natural Ecosystems - both wetlands and non-wetlands, including natural production from them.
6. Recreation - including sport fishing, hunting, boating, swimming, camping.
7. Shore/Land Development - for all purposes; industrial, commercial, or residential.
8. Waste Disposal - solid, liquid, and gas from all sources.
9. Water Supply - both drinking and industrial.

These uses have been listed in alphabetical order to avoid any suggestion of rank ordering, since their relative importance may vary from region to region. There is one, however, that will almost always be

at or near the top of any prioritized listing - waste disposal. This is because virtually all of the waste products of nature as well as man must ultimately go to the sea and, in so doing, must pass through the estuarine and coastal zone. Man can alter the timing of the transport and the form of the materials but not the basic action. This alteration may be very beneficial, however, especially when the products are a direct result of man's other activities.

As an example, Wolman, et al. (1957) estimated that some 1.7 million cubic meters of silt are deposited annually in the Potomac River near Washington, D.C. There is probably little that man can reasonably do to significantly alter this state of affairs in the near future in view of the character of the upland drainage basin, the flashy nature of the flow stream (the observed range is from under 23 cubic meters per second to over 14,000 cubic meters per second), and other natural factors. By comparison, the practice of using the upper Potomac Estuary as the final stage of the major Washington Metropolitan Area sewage treatment plant is both intolerable and much more easily remedied. Waste management concepts for the coastal zone have been deemed of sufficient importance to warrant a monograph on the subject by the National Academy of Sciences/National Academy of Engineering (1970).

Of course the list of nine fundamental uses of the estuarine and coastal zone is not without internal conflict, i.e., some uses interfere with or impact on other uses, and any given project (activity) may well involve several uses. It is in dealing with the various problems associated with such uses that the thrust of our management attention must be focused. The passage of the Coastal Zone Management Act of 1972 (PL 92-583) first set in motion the machinery for comprehensive management of all resources in the estuarine and coastal zone including the Great Lakes. The Act also provides for substantial financial assistance to eligible states and territories to develop and

administer a comprehensive management program. The program, as defined by the Act, "Includes, but is not limited to, a comprehensive statement in words, maps, illustrations, or other media of communication, prepared and adapted by the State ... setting forth objectives, policies, and standards to guide public and private uses of lands and waters in the coastal zone." [Section 304 (g)]

PROBLEMS ASSOCIATED WITH USES

Turning now to the problems associated with coastal zone use, it would appear that they can be logically grouped into four areas - institutional, socio-economic, technological, and natural. Problems in the institutional area are associated with such matters as regional integration of waste systems; interbasin transfers; vessel waste control; restrictive zoning; overlapping jurisdictions; divided authority; trade regulation; limitations on public financing; licensing inconsistencies; diverse agency objectives; uncertainty of shore ownership; private property rights; and inadequate planning, regulation, and control.

Socio-Economic problems are concerned with public attitudes towards growth, environmental control, reuse/recycle, and specific and substitute products; demand for energy, land, construction materials, water supplies and services; increasing industrial activities, levels of trade, bonded indebtedness, land values, leisure trend, and population density; overuse of resources; unsatisfactory pricing policies; and uncertain benefits to the community; to name a few instances.

Technological problems are associated with the behavior and effects (possibly synergistic) of effluents; definition of optimum water quality; water storage availability; combined sewers; adequacy of waste treatment processes; cleanup of oil and hazardous material spills; identifying and controlling non-point discharges; ineffective septic systems; microbial control; controlling runoff and sedimentation;

pollution of surface and ground waters; shore protection; physical alterations for other uses (draining, dredging, filling); shipping, including increasing vessel size and the effects of man-made obstructions; inadequate or outdated facilities and equipment; mariculture practices; pest control; determining and meeting proper environmental standards; and so on.

Natural problem areas include natural material transport; sedimentation and shore erosion; flooding; storms; natural water quantity and quality; pest and nuisance flora and fauna; predators and disease; flushing characteristics; diurnal and seasonal variabilities; and availability of suitable areas, deposits, etc.

DATA NEEDS FOR MANAGEMENT

The management process for a particular project involves determining, for the involved problem set, those uses identified with the project; identifying the impacts, conflicts, and alternative measures available; gathering, reviewing, and interpreting the required data; and finally, in consonance with overall objectives, policies, and standards, arriving at a sound decision regarding project implementation. There are also data requirements for the more general management functions of establishing objectives (including sectoral goals and targets), determining policies, setting standards, and insuring that these are followed and met within a dynamic implementation system that is workable and allows for user feedback. A review of the list of estuarine and coastal zone uses and the problem areas just discussed reveals that many of the data needs of general as well as project-specific management programs are the same, and it is to them that we now turn our attention.

Within the natural sciences, the required information or data comes from such disciplines as meteorology, hydrology, oceanography, geology,

geography, etc. Since the presence of relatively large quantities of water is an essential quality of the estuarine and coastal zone, it is not surprising that knowledge of (and the ability to predict) water quality, quantity, and motion characteristics is required for almost all management activities. Of these characteristics, the most important data need concerns total solids content. In this report these solids will be referred to as sediment, regardless of whether they are naturally occurring mineral particles or man-induced substances which are totally artificial to the water flows. They may range from toxic or hazardous substances arising from industrial activity to benign beach sand brought in from the sea. The concern is with the presence of these sediments, their sources, distribution, and ultimate fate or disposition. The remainder of this report will be addressed to this most important data requirement area for wise, efficient, and efficacious management of estuarine and coastal areas.

SECTION II

SEDIMENT MECHANICS

The mechanics of polydisperse systems such as suspended solids in fluvial, estuarine, and coastal flows are among the most complex and least thoroughly understood of all aspects of science. This is not surprising when one considers that it covers dynamic processes ranging from such sedimentology subjects as the movement of beach sand to the thixotropic world of colloid chemistry. With complete descriptions having to account for such topics as electrokinetics, descriptive and structural rheology, sorption, flocculation, diffusion, and Brownian motion as well as such hydraulic current system influences as periodic surface changes due to the forcing tides at the mouth of an estuary and the corresponding shear forces generated due to boundary resistance, gravitational forces due to density differences of fresh and sea water (which lead to internal circulation) in addition to those causing fresh water transport in the first place, and transverse centrifugal forces resulting from flow reversals in curved sections and Coriolis forces induced by the earth's rotation, it is little wonder that empirical progress has outpaced analytical descriptive efforts. The U. S. Army Corps of Engineers Tidal Hydraulics Committee (1950) recognized this complexity some time ago and set forth many of the variables that must be accounted for in a unified approach. Even under well controlled laboratory conditions, the study of suspended solid laden flows remains very difficult, with considerable data scatter the rule and statistical treatment of results being usually required. The point of all of this is not to suggest that any attempt to seriously study the subject is doomed to failure but, rather, to point out that one should not approach it as though it is a ± 1 percent cosmos.

Because of the importance of the subject as discussed in the preceding section of this report, it has been extensively studied, and the literature on the field is voluminous. The purpose of this section is not

to review the literature or present the current state of the art but, rather, to point out some of the system characteristics as they affect data gathering and interpretation. The term sediment will be used here to include all naturally occurring solids as well as those resulting directly or indirectly from man's activities. It will also be used to encompass particles of all hydraulic size*, ranging from large stones (meters per second) to colloidal clays (centimeters per century).

SEDIMENT SOURCES

In general, sediment reaching the estuarine and coastal areas either arrives from uplands, is generated within the area itself, or is carried in from the sea. In terms of overall quantity, the sediment reaching the coastal zone is primarily derived from the physical and chemical disintegration of the earth's crust. The particles vary in specific gravity and mineral composition. The predominant mineral overall is quartz; the most common clay minerals are kaoline, illite, and montmorillonoid (the hydrous silicates of aluminum, iron, and magnesium). Once the sediment particles are detached, they are transported by gravity, wind, or water or a combination of these agents. The act of removing the particles from their resting place is termed erosion.

The so-called sheet erosion occurs when fine grained silts and clays are removed from the surface in a sheet of relatively uniform thickness by raindrop, splash, and sheet flow. The movement of the sediment particles and the energy of the falling raindrops compacts and partially seals the soil surface, thereby decreasing infiltration and increasing amount of sheet flow available to erode and transport sediment. Thus, among the factors influencing the amount of material removed by sheet

* Hydraulic size is defined as the velocity of uniform fall of a particle in a quiescent fluid (distilled water at 24°C is the standard) of infinite extent.

erosion are surface slope, precipitative intensity and drop size, soil type, and vegetative cover.

Sheet flow does not occur continuously over large areas due to irregularities in the land surface. Rather, it quickly concentrates into small rills or channels and streams which grow in size as one proceeds down the drainage basin. Within these channels, the water continues to erode material until it contains as much sediment as its energy allows it to carry. Many other kinds of mass wasting or gravitational transfer of sediments towards and into streams may also take place ranging from slow creep through bank caving to landslide. To a lesser extent, particles are carried to the stream by wind.

Although the portion of sediment attributable either directly or indirectly to man's activities is less than that due to natural causes, it is frequently much more harmful due to its polluted nature. Knowledge of the character of the urban environment leads one to the expectation that stormwater draining from it will be of poor quality. Washings from the sidewalks, streets, alleys, and catch basins are a part of the runoff and include significant amounts of human and animal refuse. In industrial areas, chemicals, fertilizers, coal, ores, and other stockpiled products are exposed to rainfall, so that a significant quantity of these materials appears in the runoff. Extreme quantities of organic materials such as leaves and grass cuttings often appear in storm sewers and streams. Often during storms large boards, limbs, rock, and every imaginable kind of debris appear in the flow. Here also, one of the heaviest pollution loads is that of eroded silts and sediments washed from the land surface. Much of this is from construction areas where the land has been disturbed prior to completion of streets and buildings and re-establishment of plant life. Finally, a significant amount of solids found in storm runoff originates as dustfall from air pollution. According to studies made in Chicago and reported by the American Public Works Association (1969), about 3 percent of the total solids load has its source in dustfall.

To provide a better "feel" for the contribution of an urban area, Radziul (1965) reports that, "The City of Philadelphia with a population of 2 million on a land area of 130 square miles like other large cities typically produces:

1. 3,150 tons/day of pollution emissions
2. 861,000 tons/yr of trash
3. 90,000 tons/yr of garbage
4. 618,000 tons/yr of incinerator residue
5. 26,000 tons/yr of debris from inlets
6. 92,000 tons/yr of street sweepings
7. Replacement of 50 - 70 miles of asphalt paving
8. Wear from 4.4 million pairs of shoes
9. Erosion from 650,000 buildings
10. Droppings from 250,000 animals
11. Wear from 2.4 million tires, etc.

The above directly or indirectly affect the quality of water courses as do the effluents from municipal and industrial waste water treatment plants."

Industry, while not the largest contributor in terms of overall volume, is the source of most of the exotic (and potentially most damaging) contributors. Very few industrial processes do not require water, a fact that both accounts for plant siting near sources of water as well as for the need to dispose of water once used. These liquid industrial wastes may carry such a staggering variety of pollutants that a partial listing serves little useful purpose. There may be problems even for constituents that are present in minute quantities due to mechanisms in the area that serve to concentrate and enhance a particular substance. As a result of the Federal Water Pollution Control Act Amendments of 1972 (PL 92-500), more and more industrial dischargers are improving practices and treatment of their wastewater, but zero discharge remains a distant goal, and this situation will exist for some time to come.

The impact of man's activities on sediment received by the coastal zone is not limited to industry and the urban setting, however. It is also

a function of his general land use and housekeeping practices. Agriculture, silviculture, animal husbandry, and the like all affect both the nature and amount of sedimentation that will result from a given land area. Resource recovery practices ranging from strip mining to ore processing affect sediment yields as do projects related to flood control, hydroelectric power generation, etc.

The sea itself is also a source of sediments that arrive in the estuarine and coastal zone. Some of these are of natural origin, but again the most harmful ones are more often attributable to man's activities. They range from discharges associated with shipping (either accidental or intentional) to sludge returns from improperly designed or located outfalls. In summary, there are few of nature's actions, and virtually none of man's, that do not directly or indirectly affect the quantity and quality of sediment received by the estuarine and coastal zone.

SEDIMENT CHARACTERISTICS

As was just noted, upland discharges are often the primary source of sediment in estuaries, the material being brought in continuously in the form of suspended and dissolved solids. It was also suggested earlier that chemical action may re-precipitate some of the sizable amounts of dissolved minerals into fine particles which subsequently participate in forming shoals. The character of sediment may be discussed by chemical and size analysis, both of which may vary widely from one estuary to another. For example, Ippen (1966) reported that shoals in the Delaware estuary are composed largely of silicon dioxide with particle sizes so small that 95 percent by volume passes a 200-mesh sieve (0.07 mm) and only 5 percent by volume (or 25 percent by weight on a dry basis) may be classified as sand. By contrast, at the mouth of the Columbia River the outer bar region and jetty channel are very much affected by sand, much of which is carried as bed load from upland sources. The median grain size of this sand is approximately 0.5 mm. In a study of the characteristics of shoaling sediments in the San Francisco Bay,

Krone (1963) found that they contained particles in the clay size range amounting to approximately 60 percent by weight, with the remaining portion in the silt class. Analysis showed that in the size range of less than 2 microns, the sediment consisted primarily of illite, montmorillonite, and kaolinite minerals, with small amounts of quartz and chlorite.

From the foregoing, it is obvious that it is desirable to have standard terms that carry definite notions of particle size. Such a listing, taken essentially from a table published by the Federal Inter-Agency Sedimentation Project (FIASP;1941a) for the Subcommittee on Sedimentation of the Inter-Agency Committee on Water Resources, is presented in Table 1. It preserves the Wentworth class interval of 2^n mm except for the smallest particles, but subdivides the silt classification as suggested by Udden and Straub, and the clay classification as suggested by Udden except for the addition of the term ultra clay by the writer.

Although the terms in Table 1 are very useful for certain fields such as soil mechanics and geology, they do not present as much information about the behavior of the particle in water as others might. First, sediment particles are not spheres but are actually of innumerable shapes and degrees of angularity and, second, not all particles are of the same specific gravity, especially those more directly associated with the activities of man. In regard to the first point, sieves with square openings of uniform dimensions express a size value that becomes more and more misleading as to true particle volume as the shape of particle deviates from a sphere. This volume, together with specific gravity as mentioned in the second point, determines the mass of the particle and, hence, is one predictor of its behavior in a hydrodynamic force field. As has been noted by numerous workers (e.g., Shelley and Kirkpatrick; 1973), the use of hydraulic size (W), which is the average rate of fall that a particle would finally attain if falling alone in quiescent distilled water of infinite extent at 24°C , as a descriptor for a particle involves its volume, shape and density. It is presently considered to be the most significant measurement of particle size.

TABLE 1. SEDIMENT CLASSIFICATIONS TERMS

Size Range (MM)	Major Division	Subdivision
Above 256	Boulders	-
256 - 128 128 - 64	Cobbles	Large Small
64 - 32 32 - 16 16 - 8 8 - 4	Pebbles	Large Medium Small Very Small
4 - 2	Granules	-
2 - 1 1 - .5 .5 - .25 .25 - .125 .125 - .0625	Sand	Very Coarse Coarse Medium Fine Very Fine
.0625 - .0312 .0312 - .0156 .0156 - .0078 .0078 - .0039	Silt	Coarse Medium Fine Very Fine
.0039 - .002 .002 - .001 .001 - .0001	Clay	Coarse Medium Fine
Below .0001	Ultra Clay	-

However, there are no analytical relationships to allow its computation; recourse must be made to experiment. The geometric size of a particle can be based upon its projected lengths on a set of right cartesian coordinates oriented so that a is its major axis, b is its intermediate axis, and c is its minor axis. With patience and a microscope, the lengths a, b, and c of a particle can be determined. Since the number of particle shapes is infinite, a system for classification is required. One put forth by Schulz, et al (1954) is the shape factor defined as:

$$SF = c/\sqrt{ab} \quad (1)$$

which approximately defines the shape in terms of three of a multitude of dimensions of an irregular particle. Of course, there may be rounded, angular, smooth, and rough particles all with the same shape factor.

An excellent discussion of the fundamentals of particle size analysis is given by FIASP (1957). Table 2, which is taken from data presented therein, illustrates the effect of shape factor on hydraulic size for sand particles with specific gravity of 2.65 in water at 20°C. It can be noted that while a sphere with a nominal diameter of 0.2 mm will fall only about one-third faster than a similar sized particle with a shape factor of 0.3; a sphere with a nominal diameter of 4.0 mm falls over 2-1/2 times faster than a particle with SF=0.3. For curves showing temperature effects, correction tables, etc., the reader is referred to FIASP (1957).

In the absence of better data, Mkhitaryan (1959) states that the hydraulic size of a particle can be computed from the following:

$$W^{3/2} = gd^{3/2} (s.g.-1)/11.2\sqrt{\nu} \quad \text{when } 1 < Re < 30 \\ 0.1 < d < 0.6 \text{ mm} \quad (2)$$

$$W^{1.8} = gd^{1.2} (s.g.-1)/4.4\nu^{0.2} \quad \text{when } 30 < Re < 400 \\ 0.6 < d < 2.0 \text{ mm} \quad (3)$$

$$W = 0.875\sqrt{gd(s.g.-1)} \quad \text{when } Re > 400 \\ d > 2 \text{ mm} \quad (4)$$

where d is the mean particle diameter, $s.g.$ is the specific gravity of the particle material, ν is the kinematic viscosity of the fluid, g is the the acceleration of gravity, and Re is the particle Reynolds' number. Equation (2) is Prandtl's formula for a smooth channel, while equation (4) is the so-called square law.

TABLE 2. EFFECT OF SHAPE FACTOR ON HYDRAULIC SIZE (IN CM/SEC)*

Nominal Diameter (mm)	Shape Factors				
	0.3	0.5	0.7	0.9	Spheres
0.20	1.78	1.94	2.11	2.26	2.43
0.50	4.90	5.63	6.31	7.02	7.68
1.00	8.49	10.10	12.10	14.00	15.60
2.00	12.50	15.50	19.30	23.90	28.60
4.00	17.80	22.40	28.00	35.60	46.90

* Data from FIASP (1957)

For Reynolds' numbers less than unity, Stokes' Law is valid and can be written as

$$W = gd^2 (s.g.-1)/18\nu \quad (5)$$

Of course, the particle Reynolds' number can be expressed as

$$Re = Wd/\nu \quad (6)$$

and, by combining equations (5) and (6) the range of validity of Stokes' Law can be expressed as

$$Re = gd^3 (s.g.-1)/18\nu^2 < 1 \quad (7)$$

This is depicted graphically in Figure 1 with water at 15.6°C as the fluid. Here it can be noted that, in order to be within the range of Stokes' Law, the maximum particle diameter for sand with a specific gravity of 2.65 is less than 0.1 mm while for organic particles with a specific gravity of 1.05 it is about 0.3 mm.

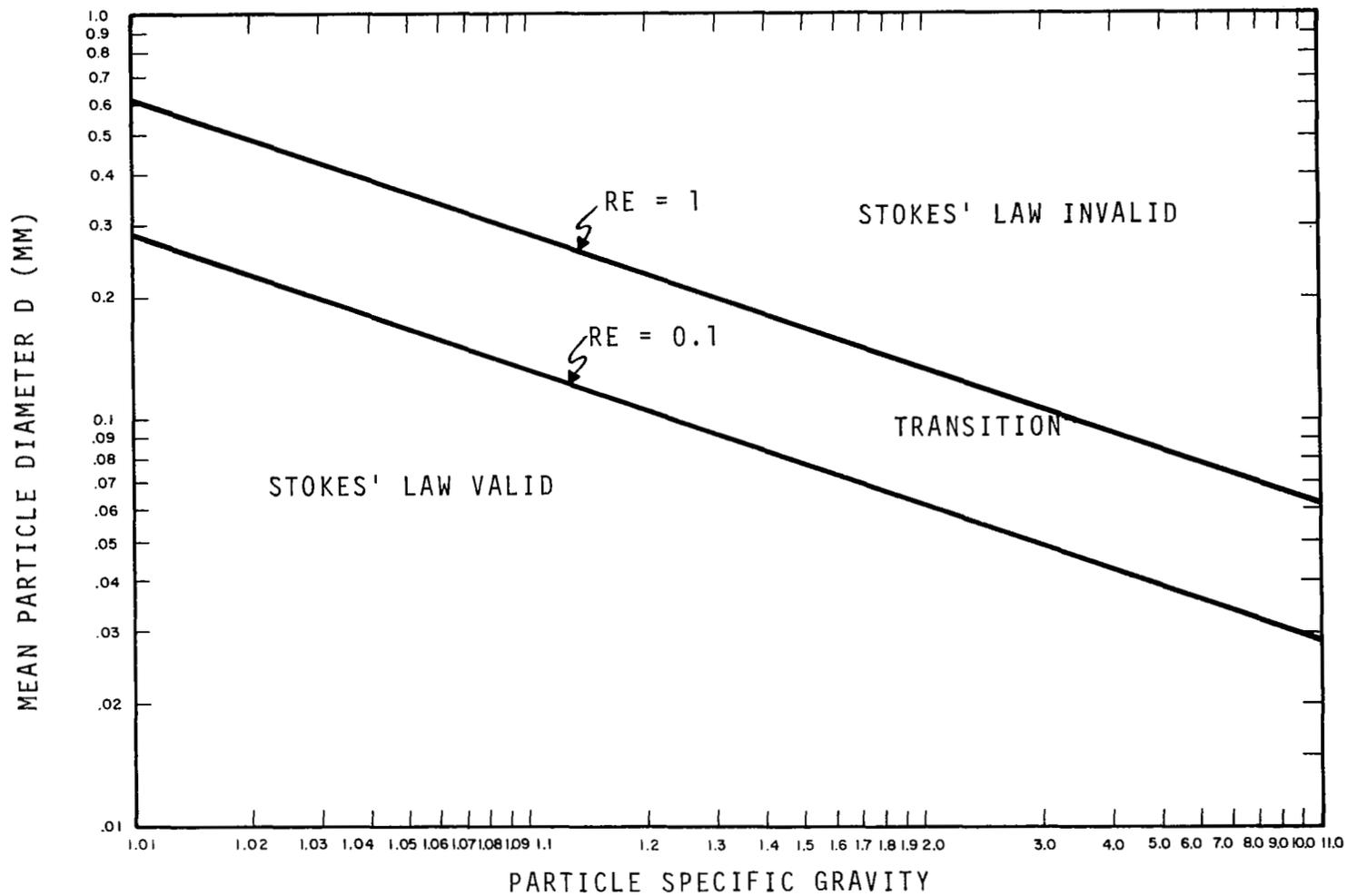


Figure 1. Region of Validity of Stokes' Law*

* Taken from Shelley and Kirkpatrick (1973).

Since the kinematic viscosity of water is temperature dependent, the Stokes' Law particle diameter limit will also be a function of temperature. A typical plot of this variation is given in Figure 2 for sand with a specific gravity of 2.65 and $Re=1$. Here it can be noted that a decrease in water temperature from the upper eighties to the mid-forties results in a 50 percent increase in the Stokes' Law limit particle diameter.

The use of hydraulic size as a descriptor for sediment particles is useful down into the clay range. For smaller particles, shape factor is no longer as important, and fall velocities become so slow that they no longer serve as such a useful descriptor, being better stated in centimeters per century. For sediment particles larger than very small pebbles, fall velocities become very large (and difficult to measure) and, consequently, are not as useful a descriptor as for the smaller particles.

Table 3 has been prepared to give a better appreciation of sediment orders of magnitude and characteristics. Eight decades of particle sizes are covered, and nominal dimensions are given in millimeters, microns, and angstroms as some readers may have a better appreciation for size in one set of units rather than another. The changes in particle weight (or mass or volume) with size are indicated relative to a 1 mm particle. Changes in hydraulic size with mean particle diameter are indicated relative to a quartz sphere (s.g. = 2.65) 1 mm in diameter. Within the range of validity of Stokes' Law they vary with the square of the diameter. The displacement due to Brownian motion relative to a 1 mm diameter particle is also indicated.

The major divisions of particle size classification set forth in Table 1 are indicated, as is the physical nature or phase of the mixture. Several other characteristics of particle-water mixtures are also given, including the visual appearance, methods of particle observations, separation techniques, and the form of the solids after evaporation.

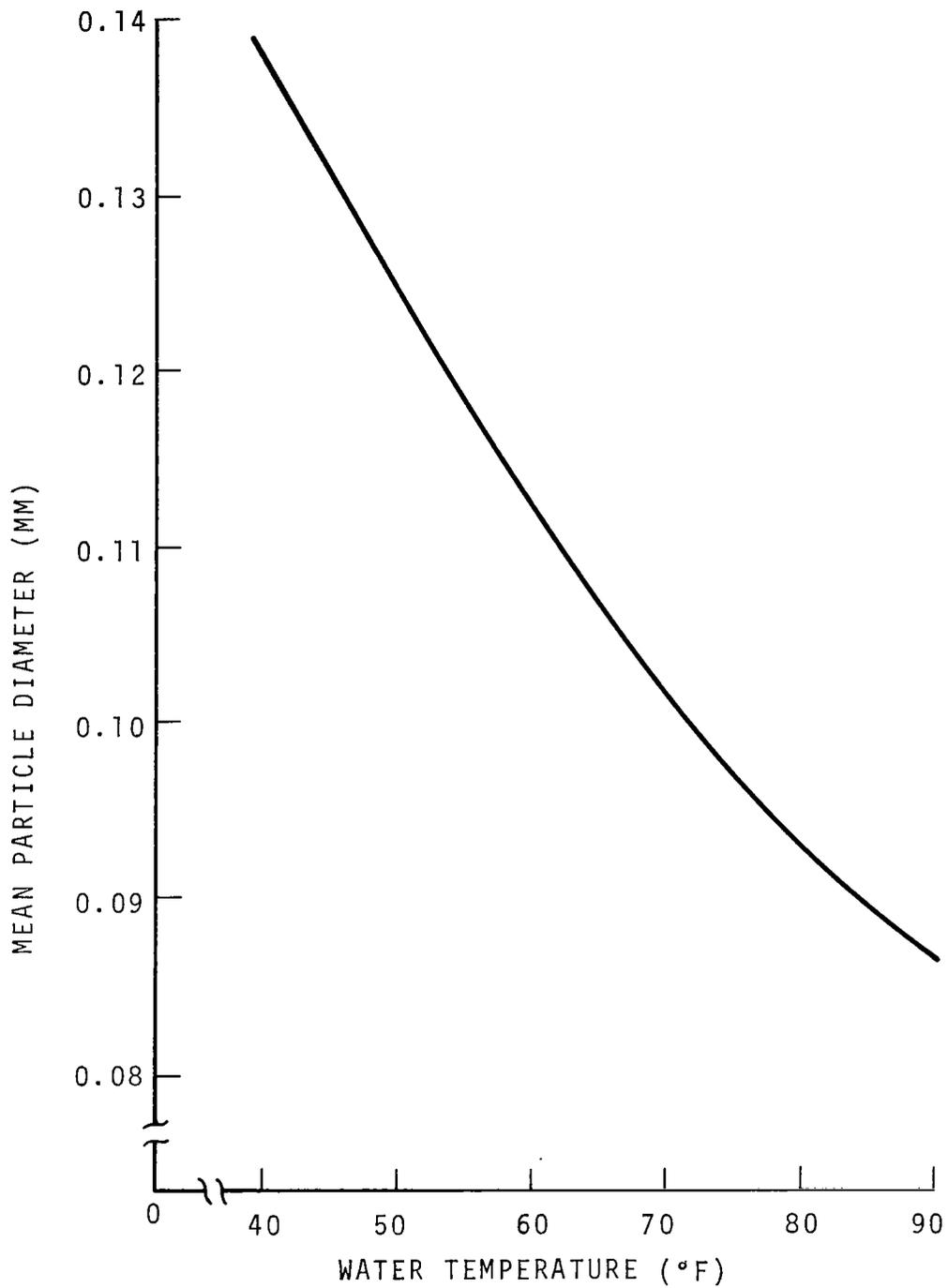


Figure 2. Effect of Temperature on Stokes' Law Maximum Particle Size*

* Taken from Shelley and Kirkpatrick (1973).

TABLE 3. SEDIMENT ORDERS OF MAGNITUDE AND CHARACTERISTICS

Millimeters	10	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
Microns	10,000	1,000	100	10	1	0.1	0.01	0.001	0.0001
Angstroms	10^8	10^7	10^6	10^5	10^4	10^3	10^2	10	1
Relative Weight of a Particle	10^3	1	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}	10^{-18}	10^{-21}
Relative Fall Velocity	4.8	1	5.6×10^{-2}	5.6×10^{-4}	5.6×10^{-6}	5.6×10^{-8}	5.6×10^{-10}	5.6×10^{-12}	-
Relative Brownian Displacement	-	1	10^1	10^2	10^3	10^4	10^5	10^6	-

Classification

Phase	bed load	coarse suspension	coll. susp.	colloidal solution	molecular soln.
Appearance	on bottom	very cloudy	turbid	virtually clear	clear
Observed w/	naked eye	naked eye	microscope	electron or ultra-microscope	-
Separated w/	screen	filter paper	clay filter	ultrafilter	-
Form after evaporation	granular	loose powder	powder or gel	gel	crystal

Notes:

1. The fall velocity of a 1 mm diameter quartz sphere is 16.0 cm/sec. Similar particles much below 10^{-4} mm in diameter essentially do not settle, their fall velocities being better stated in centimeters per century.
2. The time for average Brownian displacement of a 2 mm diameter sphere by one centimeter is around 7,300 yr. Brownian motion starts as a practical consideration for diameters smaller than 10^{-2} mm.
3. The resolution limit of an ordinary microscope is around 2000A compared to 10A for electron or ultramicroscopes.
4. The size of particles passing the finest practical sieves (300 mesh) is around 0.05 mm. The limit of an ultrafilter is approximately 10^{-6} mm.

As indicated earlier, there are characteristics of sediment particles other than size which are of interest to explain certain phenomena. For example, the charge on a particle attracts counterions and repels like-charged ions. Some of the counterions may be immobilized in the Stern layer, while the remainder form a diffuse Gouy layer. Within this double layer, the decay of potential is measured by its thickness, which is very sensitive to the concentration and valence of the counterions as is the surface charge density. Potentials at the particle surface, at the boundary between the Stern and Gouy layers, and at the hydrodynamic plane of shear are of special importance.

It has been found (e.g., Postma; 1967) that clay minerals usually have a negative charge. This may be due to preferential adsorption of anions, especially hydroxyl ions; cationic substitutions within the crystal lattice; and residual valences (broken bonds) at particle edges. The double layer of counterions (hydrated cations) described above balances the negative charge. If the electrolytic potential (thickness of the double layer) decreases below a critical value, coagulation occurs. In this process, while the double layer is present, two clay particles approaching each other by Brownian movement are repelled because their charges are equal. Other forces, however, may tend to cause the particles to approach each other. The electrolytic content of the water is a strong factor here as it affects the thickness (and hence electrolytic potential) of the double layer. As a result, although flocculation in pure river water has not been observed with certainty, clay minerals may readily flocculate in sea water, especially under the influence of magnesium and calcium ions. Increases in river pollution may cause the flocculation process to be completed far upstream of the salt boundaries, perhaps due to the presence of polyvalent cations in industrial wastes and excessive amounts of particulate organic sewage, which can act as a binding substance for fine-grained particles.

On the other hand, dissolved organic solids may inhibit flocculation, at least to some degree, as has been observed in kaolinitic clays in

particular. The electrolytic coagulation process is reversible in most instances, and marine floccules carried upstream into fresh water may be deflocculated.

The diameter of a floccule may be considerably larger than the diameters of its constituent particles, with the result that the fall velocity of flocculated clays is much greater than that in peptized form. Much water is included in the floccules, however, with the result that fall velocity increases are not as great as might otherwise be expected. For example, as pointed out by Postma (1967), a unit particle with a specific weight of 2.7 and a diameter of 5 microns has a fall velocity in seawater of about 0.002 cm/s. A particle of the same density but a 500 micron diameter would sink at a rate of approximately 20 cm/s. A floccule of clay particles of the same size but containing 95 percent water, on the other hand, would have a fall velocity of only 0.4 cm/s, the hydraulic size of a 20 micron quartz sphere.

Flocculation depends upon the nature of the mineral clays present, and different flocculation rates are observed for different mixtures. Experiments by Whitehouse, et al. (1960) have shown that the flocculation of kaolinites and illites is essentially completed at fairly low chlorinity values. For example, an increase in chlorinity from 0.5 to 2.0 percent resulted in fall velocity increases of only 1.2 percent for kaolinite and less than 18 percent for illite, and increases in chlorinity above 6 percent caused no further increase in fall velocity. On the other hand, montmorillonite, with its very stable double layer, showed a 240 percent increase in fall velocity with an increase in chlorinity from 0.5 to 2.0 percent. Further increases in chlorinity to 18 percent produced over an order of magnitude increase in the fall velocity of montmorillonite. All of these minerals seem to flocculate much more effectively than comparable size particles of quartz but, as pointed out by Ippen (1966), much remains to be learned about the flocculation characteristics of this and other minerals such as magnetite, limestone, and feldspar. Flocculation also depends upon the actual sediment concentration and the hydraulic

conditions present. The Tidal Hydraulics Committee (1960) of the U. S. Corps of Engineers provides a rather thorough treatment of the subject.

This somewhat sketchy treatment has been given to emphasize the complexity of the problem and to point out that much research remains to be done before our understanding of all of the involved phenomena is equal to the task of descriptive and predictive modeling. A second purpose has been to emphasize the importance of fall velocity, which also influences light transmission, in the overall descriptive characterization of sediment.

SEDIMENT TRANSPORT

The transport of solid particles by a fluid stream is an exceedingly complex phenomena and no complete theory which takes into account all of the parameters has yet been formulated. It normally occurs as a combination of bed movement, saltation, and suspension. Although these are interrelated, they are usually discussed separately because the phenomena are not understood sufficiently to allow one to satisfactorily consider them together. Deacon (1894), based upon observed movements of sand in connection with studies for the design of the Manchester ship canal, has provided an excellent discription of how these movements take place.

"The observations were made in a long flat-bottomed trough with glass sides, by means of which the behavior of the sand could be accurately observed. The sand was from the estuary of the Mersey, the quantities moved were weighed, and the surface velocities of the water were carefully measured. When water flowed with a steadily increasing velocity over a surface of such sand, fine pieces of broken shell were first moved; and the surface velocity required to produce such movements was considerably less than one foot per second. At such velocities, however, the sand proper was perfectly stable, and however long the flow continued it remained undisturbed; but the fine pieces of shells at the

surface of the sand moved in spasmodic leaps, accumulating wherever the velocity was somewhat less.

"The first movement of sand began at a surface velocity of 1.3 foot per second. This movement was confined to the smaller isolated grains and if the same velocity was maintained, the grains so moved ranged themselves in the parallel bands perpendicular to the direction of the current, each band taking the form of well known sand ripples of the seashore or sand-bottomed stream, with its flat slope upwards, and its steep slope downwards in the direction of the current. At this velocity the profile of each sand ripple had a very slow motion of translation, caused by sand particles running up the flatter slope and toppling over the crest. The steep downward slope was therefore being constantly advanced at the expense of the denudation of the less steep upward slope. At the surface velocity of 1.5 foot per second, the sand ripples were very perfect, and travelled with the stream at a velocity of about the $1/2160$ part of the surface velocity of the water. At the surface velocity of 1.75, the ratio was reduced to about $1/1050$, and at a surface velocity of 2 feet to $1/480$. A critical velocity was reached when the surface of the water moved at 2.125 feet per second, when the sand ripples became very irregular, indicating greatly increased unsteadiness of motion of the water. Up to this point the whole amount of scour was represented by the volume of the sand-waves multiplied by an exceedingly low velocity, always less than the $1/480$ part of the surface velocity of the water. At about this critical velocity of 2.1 feet per second, the particles rolled by the water up the flat slope, instead of toppling over the steep slope, were occasionally carried by the water direct to the next crest; and as the velocity of the water was gradually increased, an increasing bombardment of each crest from the crest behind it took place. At about 2.5 feet per second, another critical velocity was reached, and many of the little projectiles cleared the top of the first, or even of the second crest ahead of that from which they were fired. At surface velocities of 2.6 to 2.8 feet per second, the sand ripples became more and more ghostlike, until, at 2.9 feet per second, they were wholly

merged in particles of sand rushing along with the water in suspension. After this the scour was of totally different character; the sand and water became mixed, and a constant process of lifting, carrying, and depositing of individual particles ensued, the sand being stirred to a depth and lifted to a height dependent upon the velocity."

Gilbert (1914) has given another description of the process by which material is moved in streams.

"Streams of water carry forward debris in various ways. The simplest is that in which the particles are slidden or rolled. Sliding rarely takes place except where the bed of the channel is smooth. Pure rolling, in which the particle is continuously in contact with the bed, is also of small relative importance. If the bed is uneven, the particle usually does not retain continuous contact but makes leaps, and the process is then called saltation. With swifter current leaps are extended, and if a particle thus freed from the bed be caught by an ascending portion of a swirling current its excursion may be indefinitely prolonged. Thus borne it is said to be suspended, and the process by which it is transported is called suspension. There is no sharp line between saltation and suspension, but the distinction is nevertheless important, for it serves to delimit two methods of hydraulic transportation which follow different laws. In suspension the efficient factor is the upward component of motion in parts of the complex current. In other transportation, including saltation, rolling, and sliding, the efficient factor is in motion parallel with the bed and close to it."

The distribution of sediment in a transport stream is expressed in terms of concentration in one of two ways. Spatial concentration is defined (FIASP; 1963) as "the quantity of sediment relative to the quantity of fluid in a fluid-sediment mixture." Thus, it could be expressed as the dry weight of sediment per unit volume of water-sediment mixture. There

are three such concentrations that may be of interest: spatial concentration at a point in the cross section, which is the sediment concentration in a small volume at the point; spatial concentration in a vertical, which is the sediment concentration in a small water column extending from the stream bed to the water surface; and spatial concentration in a cross section, which is the sediment concentration of the mixture contained in a unit length of channel at the cross section. Turbidity, density, and other fluid properties of the water-sediment mixture are related to the spatial concentration.

On the other hand, the discharge-weighted concentration is defined as the quantity of sediment relative to the discharge of the fluid-sediment mixture. Thus, it could be expressed as the dry weight of sediment in a unit volume of discharge, or the ratio of the dry weight of sediment discharge to the weight of the water-sediment discharge. Again there are three such concentrations that may be of interest: discharge-weighted concentration at a point in the cross section which is the sediment concentration in the water-sediment discharge through a small cross-sectional area at the point; discharge-weighted concentration in a vertical, which is the sediment concentration in the water-sediment discharge through a unit width cross-sectional area centered on the vertical; and discharge-weighted concentration in a cross section, which is the sediment concentration in the discharge through the entire cross section. The discharge-weighted concentration may be multiplied by the overall stream discharge to obtain sediment discharge.

Although a number of theories on the suspension of sediment in flowing water have been proposed, it is now generally recognized that it is directly related to turbulence of the flow as explained by Lane and Kalinske (1939, 1941). In turbulent flow the instantaneous current vector has vertical and lateral components as well as the horizontal one,

and these are constantly changing in magnitude and direction with time in a random fashion. As expressed in FIASP (1963):

"Sediment carried in suspension is acted on in the vertical direction by momentary currents which move upward or downward in the stream. Because the water level in the stream remains unchanged, the quantity of upward and downward flow must be equal. If the upward and downward currents were the only forces affecting the vertical movement of sediment, complete mixing would soon take place and the concentration of sediment would become uniform throughout the depth. However, all particles of specific gravity greater than that of water settle steadily downward. Under the combined action of vertical currents and gravitational force, a particle caught in a current moving upward at a rate greater than the settling velocity of the particle should be transported upward, but if it is suspended in water moving downward, or moving upward at a rate less than its settling velocity, the particle should move downward. It might seem that the downward currents would take down as much sediment as the upward ones carry up, with the result that all the material finally would settle to the bottom. However, as settling takes place the sediment concentration increases toward the bottom, and the upward currents travel from a region of higher concentration to one of lower concentration, whereas for the downward currents the opposite relation prevails. As the amounts of water moving upward and downward are equal and the sediment concentration in the rising currents is potentially greater than in the downward currents, more sediment must be acted upon by the rising than by the falling currents. The settling action superimposed on the fluctuating upward and downward currents tends to produce a balanced suspension in which the rate of increase in sediment concentration toward the bottom depends upon the degree of turbulence in the stream and the settling velocity of the suspended particles."

Since coarse particles settle faster than fine particles of the same specific gravity and the vertical water motion due to turbulence will

not be appreciably different for sediment particles of different sizes, equilibrium can only be obtained if the vertical distribution of sediment varies, with the concentration increasing more towards the bottom for coarse than for fine particles. As particle size decreases, the vertical concentration gradient becomes less and less until it is essentially zero, the case for most silts and clays. Figure 3 depicts typical distribution curves for various sizes of sediment in the Missouri River at Kansas City.

The well known Karman-Prandtl logarithmic law for the velocity distribution can be expressed in terms of the mean velocity $\bar{\mu}$ at the vertical as

$$\frac{\mu - \bar{\mu}}{\mu_*} = \frac{1}{\kappa} \left[1 + \ln \frac{Y}{D} \right] \quad (8)$$

where μ is the horizontal velocity component (time averaged) at a distance Y up from the bed, D is the flow depth at the vertical, κ is the von Karman universal coefficient, and $\mu_* = \sqrt{gsD}$ is the shear velocity with the slope of the energy gradient represented by s . Values for κ for clear water flowing over plane beds range from 0.39 to 0.43.

When sediment is present, however, the constant κ_s is neither a constant nor universal, being dependent upon the nature and concentration of the sediment. Ippen (1966) indicates that values of κ ranging from around 0.16 to 0.43 were obtained in flume studies using sand series sediments. κ was typically a constant over the upper 90 percent of the flow depth, but began to vary markedly in the region near the bed. In reporting on river flows, FIASP (1963) states that values of κ as high as 4.0 may be observed for sediment laden flow over sand-dune beds.

The sediment concentration C at some distance Y above the bottom of a stream has been expressed in the form

$$C = \left(\frac{D-Y}{Y} \right)^Z \quad (9)$$

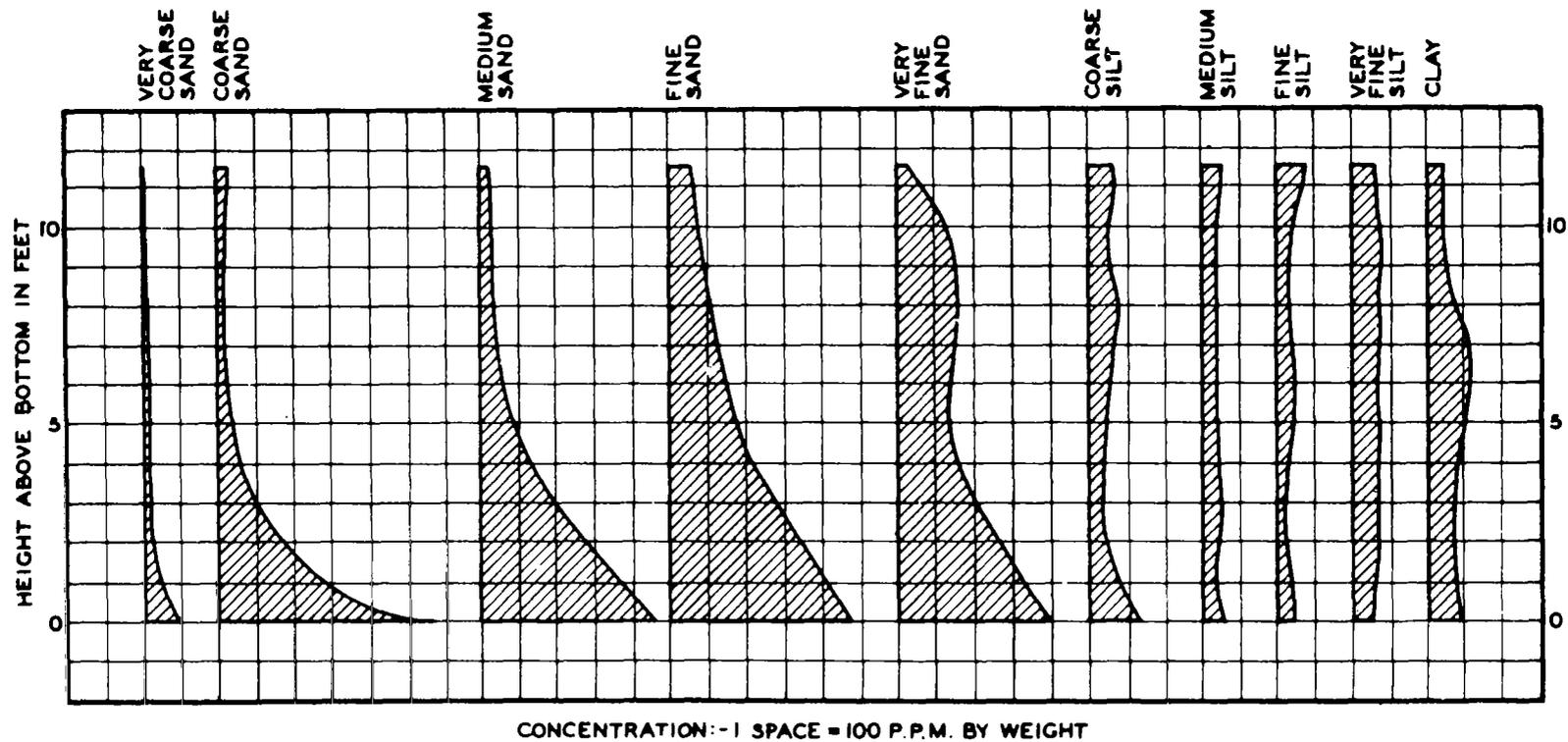


Figure 3. Vertical Distribution of Sediment in the Missouri River at Kansas City*

* Taken from FIASP (1948).

where Z is a theoretical exponent that describes the vertical distribution given by

$$Z = W/\kappa\mu_* \quad (10)$$

where W is the fall velocity and κ and μ_* are as just defined. In practice, however, the theoretical Z is not very reliable, and it is better derived from measured data. Comparisons of the mean ratios of sediment concentrations found near the mid-depth and bottom to those near the surface for a number of rivers of the United States and other countries were summarized and plotted by FIASP (1948). This has been reproduced here as Figure 4. Each value shown is the mean of a number of observations at a single station, and the number of observations at some stations exceeded 1000. Therefore, in preparing Figure 4, equal weight was not given to each observation but to the average value for each sampling station.

Examination of Figure 4 discloses that, as expected, the concentrations near the mid-depth and bottom were almost always greater than those near the surface, and those near the bottom were almost always greater than those near the mid-depth. Some 50 percent of the mid-depth samples and 77 percent of the bottom samples exceeded the surface concentration by more than 10 percent, and 30 percent of the mid-depth and 56 percent of the bottom samples exceeded the surface concentration by more than 20 percent.

For fairly long reaches of reasonably uniform channel one would expect lateral suspended sediment concentration to be relatively uniform across the stream, and observations bear this out. Figure 5, which is taken from FIASP (1948), shows the frequency of deviations of concentration from the mean for the cross section at the center and quarter points. As can be noted, lateral variation seldom exceeds ± 10 percent of the mean. This will not be true, however, below major tributary inflow, in channels with highly irregular bed forms, or just below major levels in the water course.

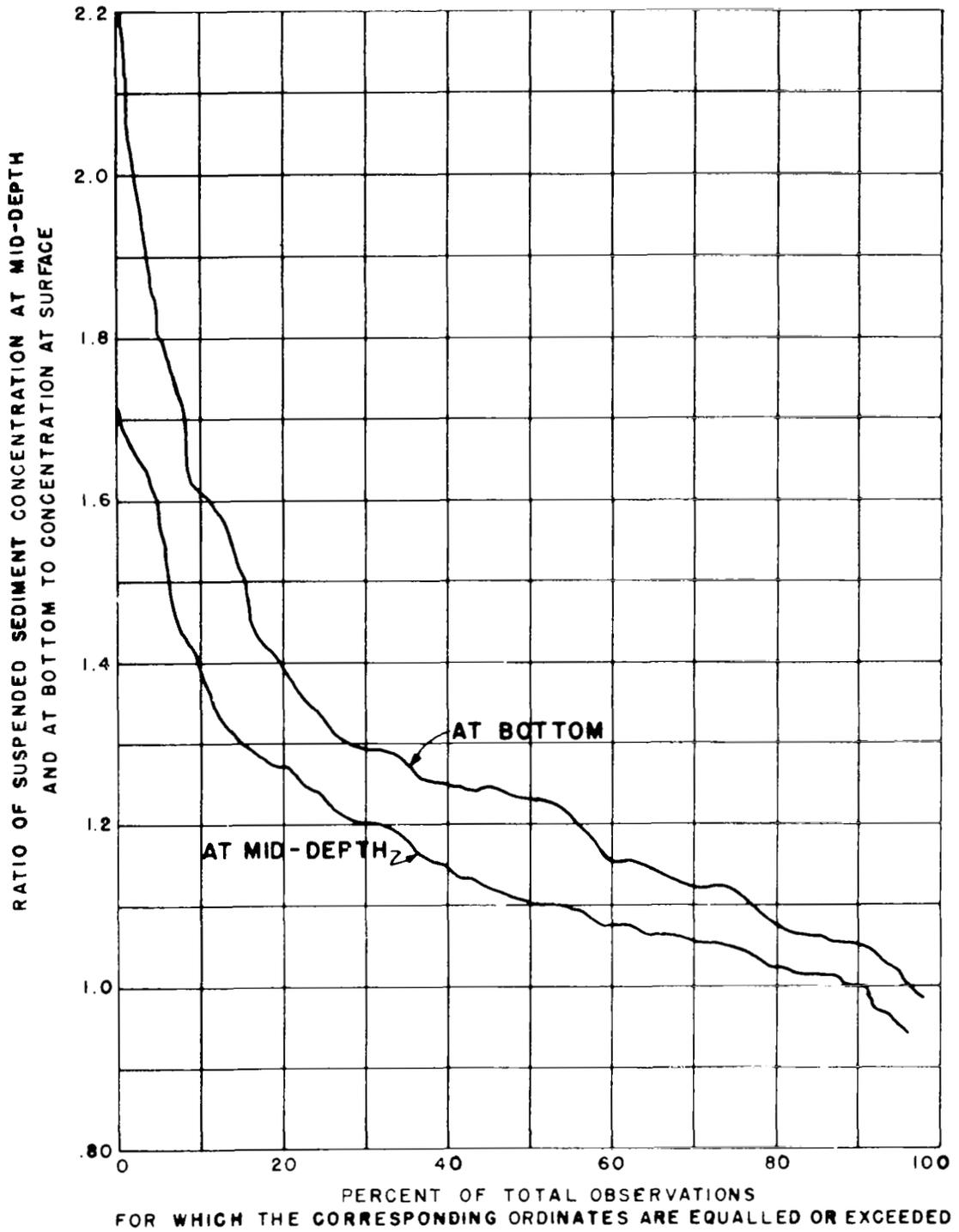


Figure 4. Observed Vertical Distribution of Suspended Sediment*

* Taken from FIASP (1948).

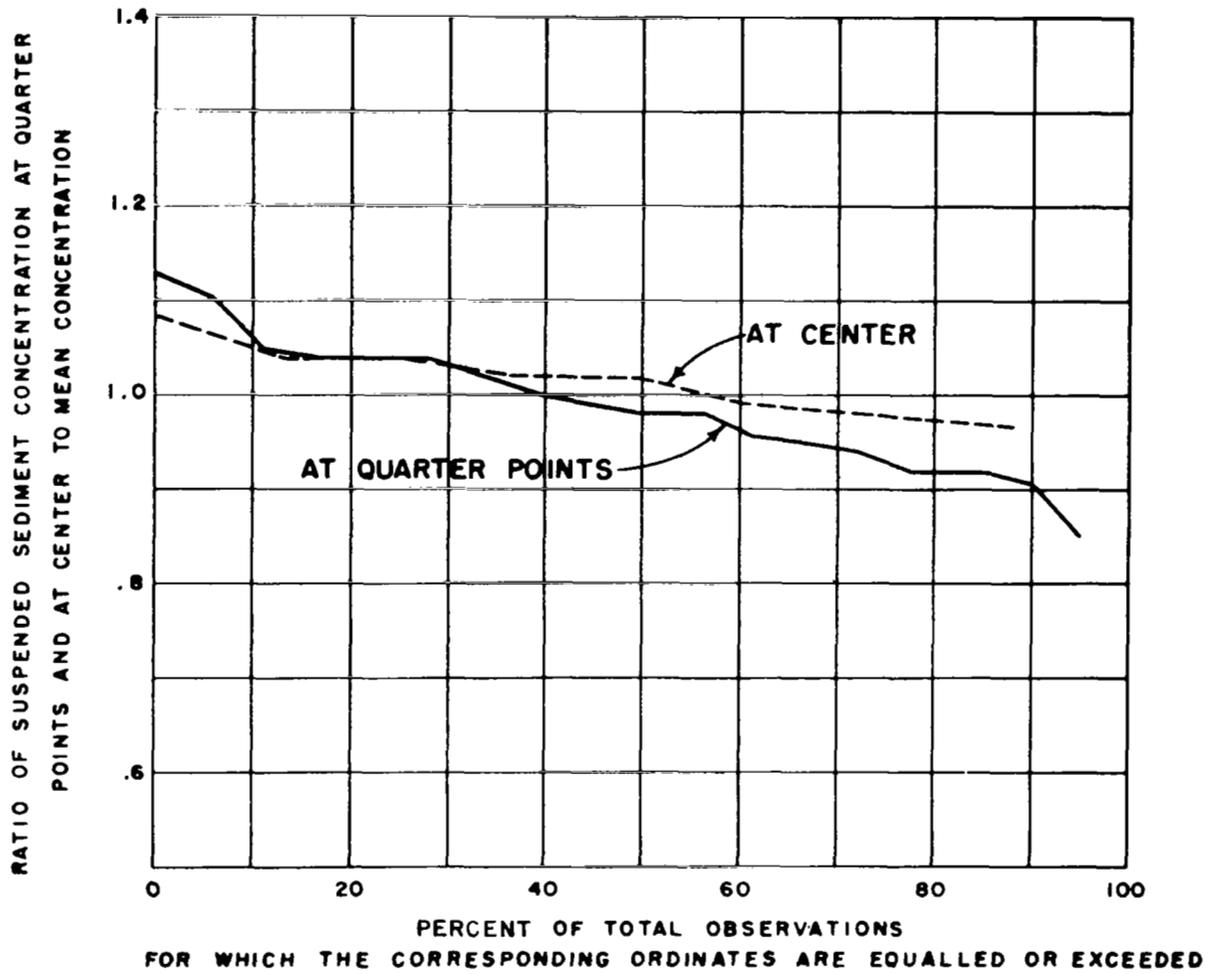


Figure 5. Observed Transverse Distribution of Suspended Sediment*

* Taken from FIASP (1948).

The discussion of sediment distribution and transport so far has been restricted to granular materials and fairly regular channels. Such granular materials presumably do not affect the viscous characteristics of the fluid-sediment mixture; i.e., we are still dealing with a Newtonian fluid. There are essential differences in dispersion and hydraulic transport between granular and colloidal materials due to the possibility of the latter flocculating and forming aggregates of particles in interaction with the suspending fluid, while granular sediments remain single regardless of flow conditions. The suspensions of colloidal and flocculated sediment frequently do not obey the simple Newtonian shear relationship, having an effective viscosity which becomes a function of the strain imposed. Such non-Newtonian fluids possess so wide a spectrum of such different characteristics that definitions of effective viscosity are lacking for most. The thixotropic property of colloidal suspensions, i.e., their ability to resist deformation to a critical shear, greatly affects their hydraulic transport, e.g., plug flow can exist, the onset of fully turbulent flow is more and more delayed with respect to Reynolds' number, resistance coefficients for the mixture are often lower than for clear water, etc.

In combination with the altered flow patterns in the coastal zone due to tidal action and oceanic influences, the transport problem becomes even more complex and, for the present purpose, space is not available to treat it even in a summary descriptive way except to note that the hydrological conditions are even more strongly coupled with meteorological events. Heavy precipitation and runoff, wind-driven waves and currents, and storm-generated surges may often override normal river circulation patterns and modify transport, mixing, and diffusion processes. In many estuaries the exchange is a two-layered system, with higher salinity water flowing upstream in the deeper portions of the channel and lower salinity water flowing downstream in the upper portions of the cross section. Thus, in addition to considerations of colloidal chemistry, one must deal with tides, currents, freshwater inflow, salinity

distributions, etc., in the study of the transport mechanisms responsible for the distribution of sediment. The reader is referred again to the writings of Ippen (1966) and Postma (1967) as well as to Simmons (1966), Phleger and Ewing (1962), Scruton (1956), Biggs (1967), Mysels (1959), and Ingle (1966).

SECTION III

DIRECT MEASUREMENT OF SEDIMENT

There are two fundamental categories, direct and indirect, into which all sediment measurement methods fall. As used in this report, direct methods involve physically sampling the water-sediment mixture and analyzing the sample (usually in a laboratory) to determine the characteristics of interest, e.g., concentrations, particle size analyses, chemical and biological analyses, etc. All other measurement techniques that do not have this "hands on" requirement are referred to here as indirect methods. Indirect measurement of sediment will be addressed in Section IV. Here we wish to focus our attention on direct measurement methods, and the sampling problem is a proper beginning.

SEDIMENT SAMPLING

With all of the analytical difficulties discussed or alluded to in the foregoing, it is obvious that there must be great reliance upon empirical data in the study of sediment transport and distribution. Unfortunately, as has been pointed out by Shelley and Kirkpatrick (1975b), it is no simple matter to gather a representative sample from a complex, flowing polydisperse system. A wide variety of sampling equipment designs is available (Shelley; 1974); but none of them is universally acceptable for representatively sampling all flows of interest (Shelley; 1975), and differences in designs and produce marked differences in results as reported by Harris and Keffer (1974) and Shelley (1976b).

The reasons for these sampling difficulties have been alluded to in the preceding discussions of sediment characteristics and transport. Let us first consider some empirical data from FIASP (1941b). In the study, a special pressurized circulating loop was assembled containing a 25 cm square test section some 4.6m long. Careful measurements of the

velocity contours were made, and near uniformity was observed. From Figure 6, which shows such velocity contours for a nominal 1.5 m/s (5 fps) velocity flow, it can be seen that the velocity 1.3 cm (1/2 in.) from the wall exceeds 1.4 m/s (4.5 fps) everywhere except near the corners. Since the variability of a pollutant will be a function of velocity variations (among other factors), it is of interest to note the horizontal and vertical variations of sediment distribution observed experimentally in this test section with its very small velocity variation.

Four readily available commercial "sands", differing principally in size, were used in the study. They are referred to by mean particle size (50 percent finer by weight) as 0.45 mm, 0.15 mm, 0.06 mm and 0.01 mm. (Note that the last two sizes are in the silt division as described by Table I and used herein.) Observed sediment distributions for the three coarsest sands are indicated in Figure 7. For all practical purposes the 0.01 mm "sand" was uniformly distributed. It should be noted here that the vertical variation is probably enhanced due to the design of the horizontally elongated test loop, which would tend to enhance concentrations of heavier particles to the outside (the bottom of the test section in this case) due to the action of inertia forces. Observations made in FIASP (1966) indicate this effect rather effectively. In their test set-up, a 2.4m wide flume was narrowed to a 46 cm test section by placing an insert in the flume bed along the wall opposite to that from which samples were to be extracted. Although the reduction in width occurred some 11m upstream of the sampler inlet, for the 0.45 mm sand used in the investigation, concentrations at 2.5 cm from the wall were found to be two to four times greater than at 7.6 cm from the wall. Similar but less pronounced horizontal concentration gradients were observed for the finer sands as well.

The observation was made in FIASP (1966) that, in addition to variations in sediment concentration within the cross-section at a given time, the sediment concentration at any point in the cross-section was highly

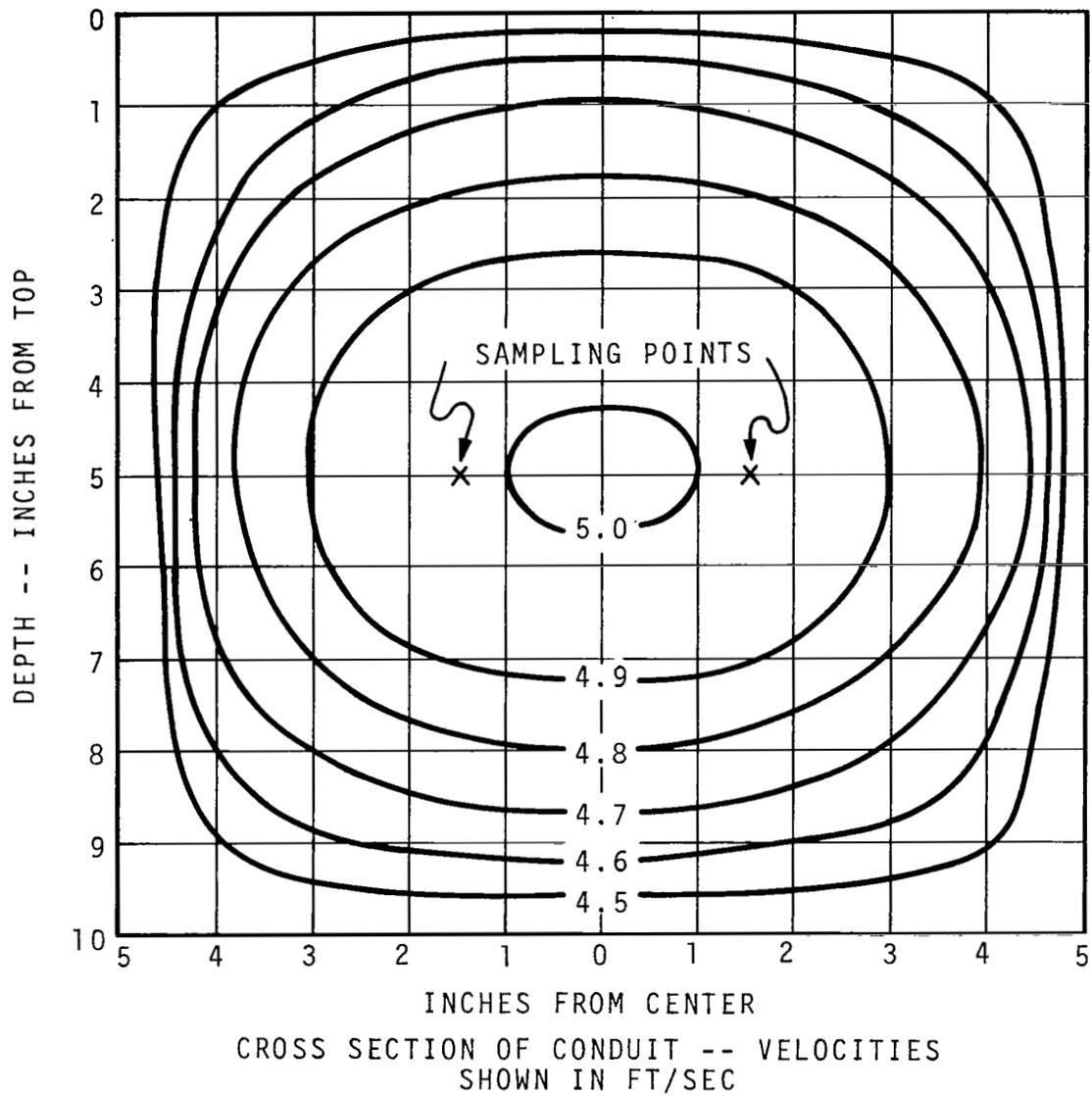


Figure 6. Velocity Contours at Sampling Station*

* Taken from FIASP (1941b).

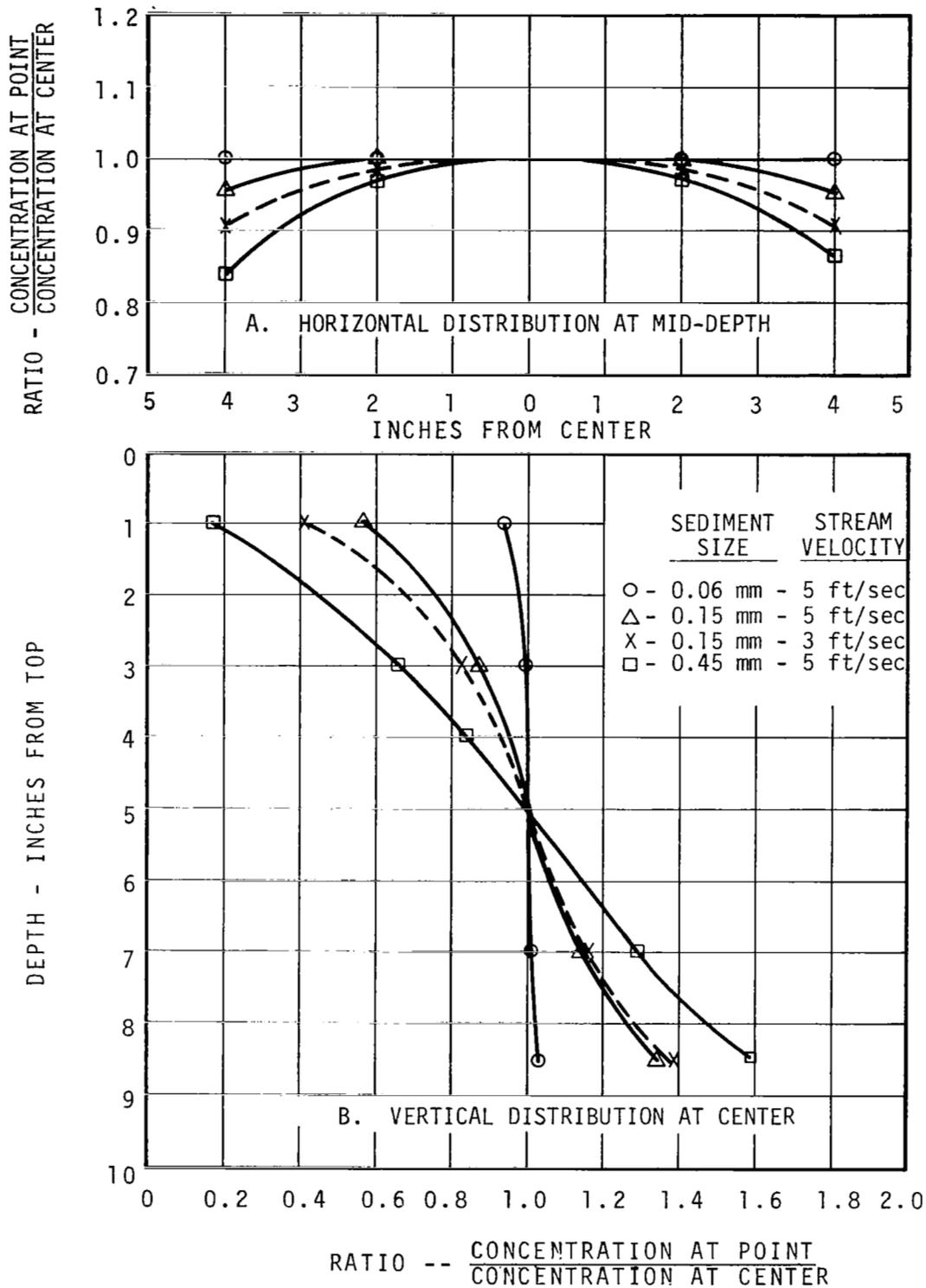


Figure 7. Sediment Distribution at Sampling Station*

* Taken from FIASP (1941b).

variable with respect to time, especially for the coarser sediments (0.45 mm). This observation was also made in FIASP (1941b) where data are presented on concentration variation with respect to time as a function of sampling interval. The concentration of successive 20-second samples was found to vary over a range of 37 percent of the mean, and the concentration of successive 60-second samples varied over a range of 10.5 percent. Such variations arise from the natural turbulence of the flow as would be encountered in a natural channel and from the non-uniform nature of recirculated flows in test loops which is peculiar to laboratory simulations.

Let us now consider the ability of a sampler intake probe to gather a representative sample of dense suspended solids in the sediment range, say up to 0.5 mm with specific gravity of 2.65. The results of a rather thorough examination of relatively small diameter intake probes (0.63 and 0.32 cm) are given in FIASP (1941b). The argument is developed that, for a nozzle pointing directly into the flow, the most representative sample of a fluid/suspended-solids mixture will be obtained when the sampling velocity is equal to the flow velocity at the sampling point. Using this as the reference criteria, investigations were conducted to determine the effects of a) deviations from the normal sampling rate, b) deviations from the straight-into-flow position of the probe, c) deviations in size and shape of the probe, and d) disturbance of sample by nozzle appurtenances. The effect of the sampling velocity on the representativeness of the sample is indicated in Figure 8 which presents the results for 0.45 mm and 0.06 mm sand. For the latter size, which falls within the Stokes' Law range, less than ± 4 percent error in concentration was observed over sampling velocities ranging from 0.4 to 4 times the stream velocity. For the 0.45 mm particles, the error at a relative sampling rate of 0.4 was +45 percent, and at a relative sampling rate of 4 the error was -25 percent.

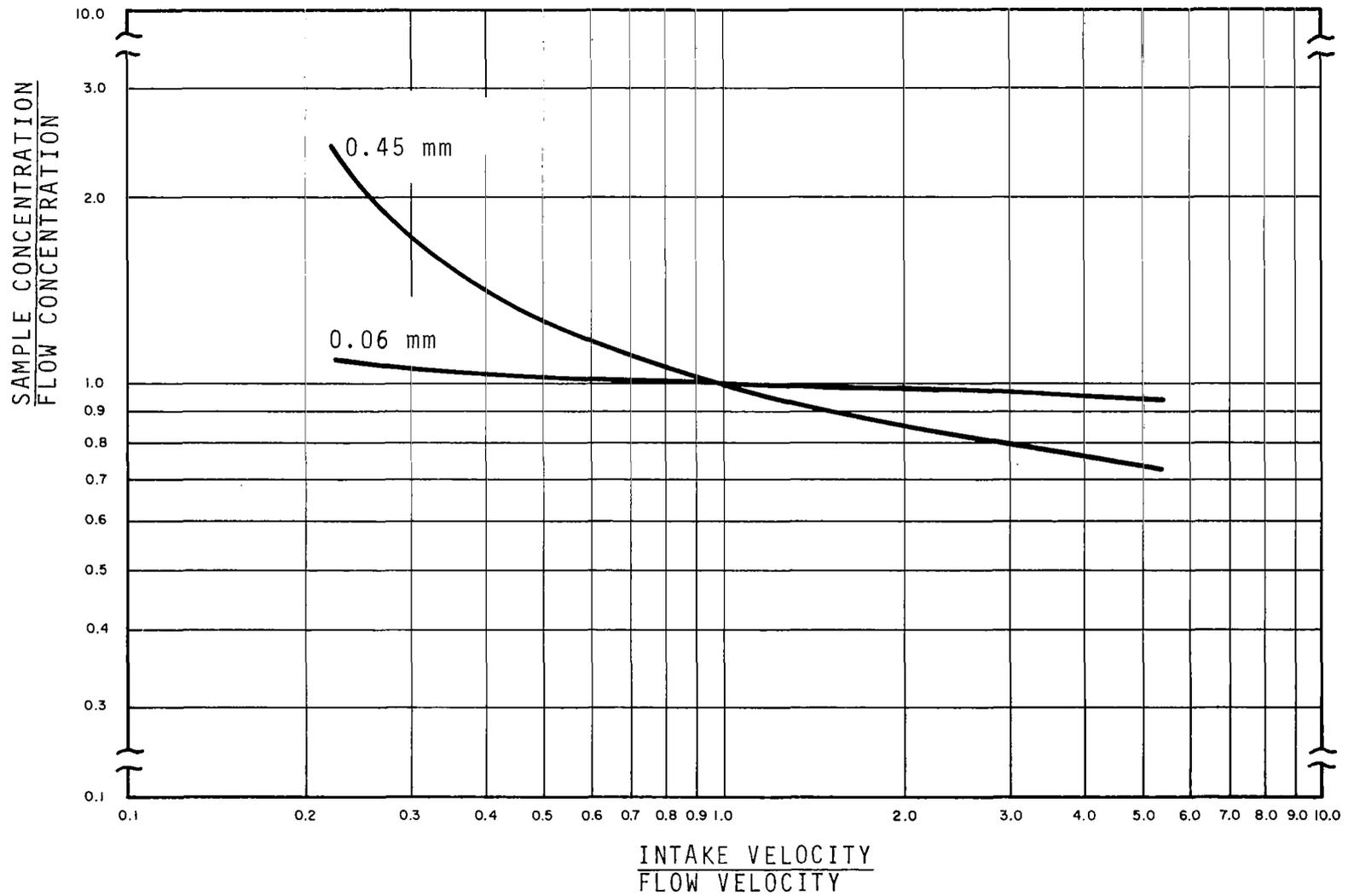


Figure 8. Effect of Sampling Velocity on Representativeness of Suspended Solids*

* Data from FIASP (1941b).

For probe orientations up to 20° to either side of head-on, no appreciable errors in concentration were observed. Similarly, introduction of 0.38 and 0.95 cm diameter probes showed comparatively little effect on the representativeness of the sample. The probe inlet geometry, i.e., beveled inside, beveled outside, or rounded edge, also showed little effect on the representativeness of the sample when compared to the standard probe. Finally, in instances where a sampler body or other appurtenance exists, the probe should be extended a short distance upstream if a representative sample is to be collected. In summary, it was found that for any sampler intake facing into the stream, the sampling rate is the primary factor to be controlled.

Tests were also run with the sampling intake probes in the vertical position to determine the effect such an orientation had upon the representativeness of the sample. With such intakes, the sample entering them must undergo a 90° change of direction, and consequently there is a tendency for segregation and loss of sediment to take place. Tests were run with the standard probe, a 0.63 cm diameter orifice in the center of a 2.5 x 5.1 cm flat plate oriented so that its longest dimension was in the direction of flow, and with an orifice in a crowned (mushroom shaped) flat plate 3.2 x 5.1 cm. The results all showed negative errors in concentration, increasing with particle size and increasing with intake velocities less than the stream rate but nearly constant for intake velocities higher than the stream rate.

Since the smallest errors were found for the orifices in the flat and mushroom shaped plates (whose performances were nearly identical for intake velocities greater than one-half the stream velocity), it was decided to investigate the effect of lateral orientation, i.e., to rotate the plate 90° so that it might represent an orifice in the side of a conduit rather than in the bottom. The results for 0.15 mm sand are presented in Figure 9. It can be noted that while the side orientation caused greater errors (as was to be expected), these errors

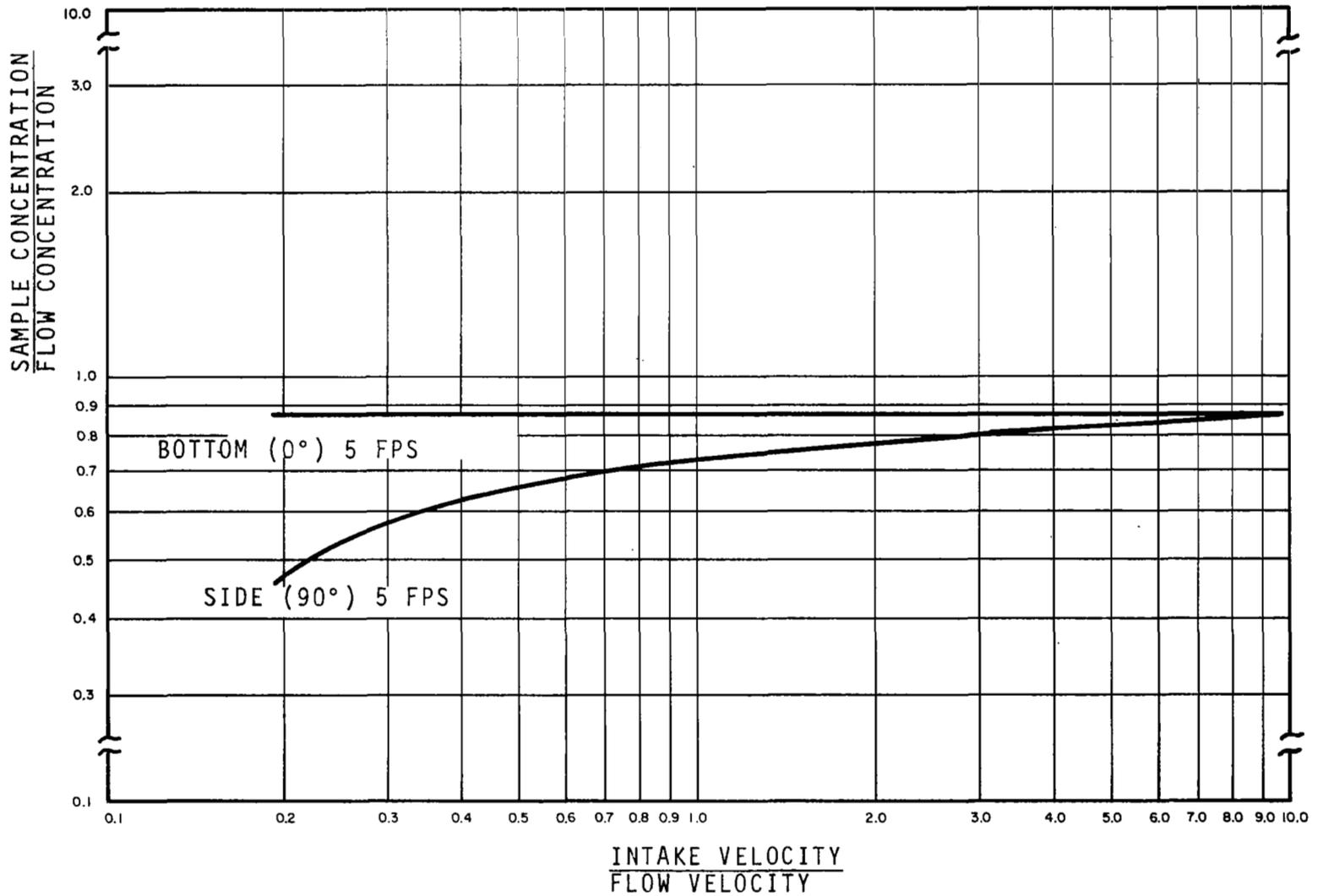


Figure 9. Effect of Lateral Orientation of Sample Intake*

* Data taken from FIASP (41b).

approached the nearly constant error of the 0° orientation as the relative sampling rate was increased above unity.

The work reported in FIASP (1966) was a laboratory investigation of pumping sampler intakes. Nine basic intake configurations, all representing an orifice of some type in the side wall of the flume, were examined. They included 1.3, 1.9, 2.5, and 3.8 cm diameter holes with square edges, 1.9 cm diameter holes with 0.32 and 0.63 cm radii, 1.3 x 2.5 cm ovals, one oriented vertically and the other horizontally, and a 1.9 cm diameter hole with a 5 cm wide shelf just under it. Sand sizes of 0.10 mm and 0.45 mm were used in the study.

Reference samples were taken with a probe located near the wall and pointing into the direction of the flow. The reference sample intake velocity was equal to the stream velocity. The primary measurement was sampling efficiency, defined as the ratio of the sediment concentration in the test sample to that of the reference sample computed for a point 1.3 cm from the wall. The reference sample was taken just before and just after the test sample was gathered. Although the data exhibited considerable scatter, several conclusions were drawn. With regard to the intake velocity, greater than 0.9 m/s is generally desirable and, for sands coarser than 0.2 mm, an intake velocity equal to or greater than the stream velocity is desirable. With regard to intake configuration, for intake velocities greater than about 0.9 m/s the sampling efficiencies showed little effect of size of intake, of rounding the intake edges, or of shape and orientation of the axis of the oval intake. Sampling efficiency was found to decrease with increasing particle size above 0.10 mm for all intakes tested. Finally, although the shelf intake showed somewhat higher sampling efficiency for coarse particles and high stream rates, its performance was very erratic over the entire range of test parameters.

Similar observations were made in field tests with river water samples at St. Paul and Dunning, Nebraska, reported in FIASP (1962). In addition to the "standard" intake which was a flush mounted 2.5 cm pipe coupling, alternate intakes included 2.5 x 5.1 cm and 2.5 x 22.9 cm nipples; a 2.5 x 22.9 cm nipple with a 0.3 cm thick steel plate 36 cm high and 43 cm wide at its end; and a 2.5 cm street elbow with a 2.5 x 5.1 cm nipple oriented down, into the flow, and up. It was concluded that the standard intake was as good as any in terms of sampling efficiency and was therefore preferable, since it offered no obstruction to the flow and was therefore less vulnerable to damage by debris. The sediment being sampled was rather fine; in high flows 88 percent was finer than 0.062 mm and 100 percent was finer than 0.50 mm.

To summarize the foregoing as it relates to the ability to gather a representative sample at a point in the flow, we note the following:

1. It becomes difficult to obtain a one-to-one representation, especially for inlets at 90° to the flow, for large, heavy suspended solids (i.e., particles of large hydraulic size).
2. For particles that fall within the Stokes' Law range, consistent, representative samples can be obtained.
3. The geometry of the sampler intake has little effect on the representativeness of the sample.
4. The sample intake velocity should equal or exceed the velocity of the stream being sampled.

Very few data needs require only the sediment concentration at a point, however. One is more often concerned with estimating total quantities or discharges. This requires measurement of flow rates and of the

sediment concentration throughout the cross section. Flow measurement is such a lengthy subject itself that it will not be dealt with at all here. The reader is referred to the recent monograph by Shelley and Kirkpatrick (1975a) for a discussion of the subject, descriptions of currently available equipment, and selected references in the literature.

The essence of the problem is contained in Figure 10, where the lengths of the arrows represent velocity, sediment concentration, or discharge as indicated. The stream velocity can be expressed quantitatively as volume per unit time and unit cross-sectional area; sediment concentration can be expressed as weight per unit volume; and thus, the product of the two equals weight of sediment discharged per unit of time per unit of area. In this fashion, the velocity distribution curve of Figure 10d and the spatial sediment concentration distribution curve of Figure 10e can be used to create the sediment discharge distribution curve for the vertical shown in Figure 10f. The mean discharge in vertical 10f divided by the mean velocity from 10d equals the discharge-weighted concentration for the sampling vertical. The sediment discharge (weight of suspended sediment passing the cross section per unit time) is represented by the volume of Figure 10c just as the stream discharge is in Figure 10a.

The problem in estimating sediment discharge is primarily one of reducing the number of point measurements that must be taken in order to adequately characterize the flow. The wide ranges in concentrations, down the vertical discussed earlier emphasizes the difficulty of selecting enough points to accurately define the sediment concentration in the vertical, without sampling so many points that the whole procedure becomes impractical. Methods used to select sampling points have ranged from thorough consideration of the principles involved to simple

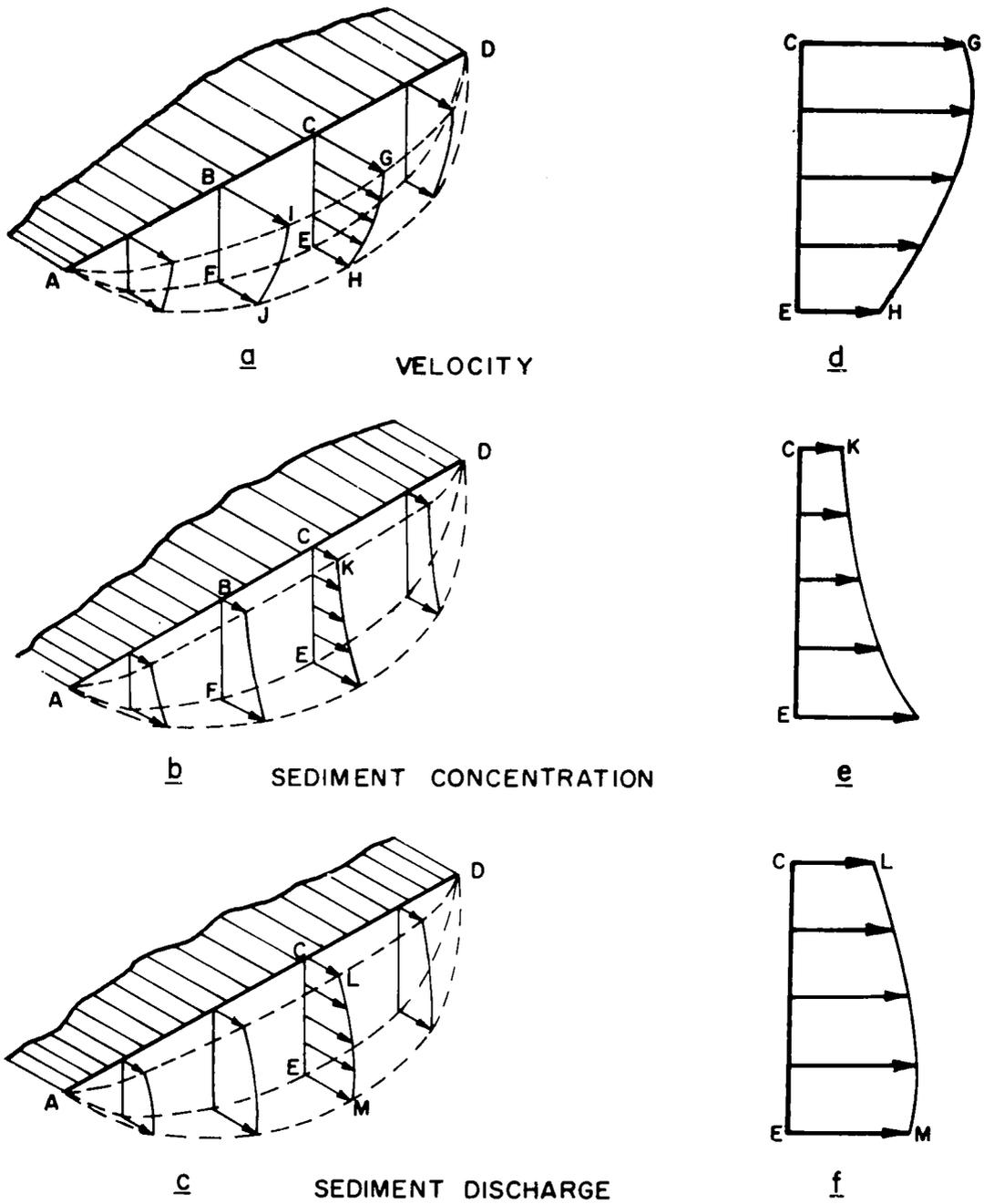


Figure 10. Velocity, Sediment Concentration, and Sediment Discharge in Streams*

* Taken from FIASP (1948).

arbitrary selection. Some of the more common methods which have been used to define the sediment concentration in a vertical are given by FIASP (1963) as:

- a. A single sample taken at the surface.
- b. A single sample taken at 0.6 depth.
- c. Two samples, one taken near the surface, and the other near the bottom, weighted equally.
- d. Three samples, taken near the surface, at mid-depth, and near the bottom, weighted equally.
- e. Three samples, taken near the surface, at mid-depth, and near the bottom, with the mid-depth sample given twice the weight of the others.
- f. Samples taken at several points to establish the vertical distribution with the required degree of accuracy.
- g. Samples taken at definite locations with corrections based on previous observations.

"The accuracy of point-sampling methods can be expected to increase with the number of samples. The simplest method, sampling near the water surface, is well suited to unskilled observers and to conditions where excessive debris and ice flows are encountered, but, because coefficients applicable to surface samples are unreliable, this method is the least accurate. Surface samples are especially undesirable for size analysis because the larger particles are usually not found at the surface of the stream.

"Sampling at 0.6 depth has been used in some streams in Texas, India, and Turkestan. This method may be satisfactory for some streams in which sediments are in the silt and clay size range, but for other streams this method would be inaccurate. This method would also be unreliable for size analyses. Sampling at two points in a vertical, near the surface and bottom, is of doubtful accuracy although it is better than sampling only at the surface. If the surface and the bottom samples have the same volume, a single analysis can be made of the combined samples.

"Of the three-point methods, the second is preferable. The mean of the upper half of the concentration will be approximated by the average of the surface and mid-depth values, and the mean of the lower half by the average of the mid-depth and bottom. Thus, in determining the mean for the whole stream, the mid-depth concentration is given a double weight relative to the bottom and surface. A composite sample made up of two samples from mid-depth and one each from the surface and bottom, all of equal volume, approximately represents both concentration and size distribution. Actually, samples cannot be taken on the bottom. The bottom sample should be taken at about 0.9 depth. The methods involving three samples are more accurate than the surface and the bottom method, and they are sufficiently simple to be handled by unskilled observers."

The proper selection of verticals is also necessary for accurate measurement of sediment discharge. Again quoting from FIASP (1963): "The common methods that have been used to locate the transverse position of sampling verticals in sediment measurements are as follows:

- a. Single vertical at midstream.
- b. Single vertical at thalweg or point of greatest depth.
- c. Verticals at $1/4$, $1/2$, and $3/4$ width.

- d. Verticals at $1/6$, $1/2$, and $5/6$ width.
- e. Four or more verticals at mid-points of equal-width sections across the streams.
- f. Verticals at centroids of sections of equal water discharge.

"The number and locations of verticals to be sampled should be governed by the degree of accuracy sought in the investigation, the size and shape of cross section, the particle size of the sediment, the ratio of the sediment discharge being carried at the time of sampling to the total sediment discharge during the period under consideration, and other characteristics of the stream. The particle size and the accuracy sought are probably of greatest importance. Although the field technique used in any sediment investigation will naturally be dependent upon the relative importance of these factors, the basic criterion for a rational sampling technique is that the sampling verticals should be located, or their mean discharge-weighted concentrations should be weighted, with respect to the transverse distribution of stream discharge. That is, either the sampling verticals should represent equal parts of the total water discharge, or the value of the mean discharge-weighted concentration for each vertical should be weighted in proportion to the fraction of the stream discharge that it represents."

A brief discussion of equipment used for sediment sampling will be given to conclude this sub-section. There has been no dearth of equipment designs for sediment sampling, some of which are good and others which are totally unsuitable for this purpose. More than 65 so-called suspended sediment samplers are described in FIASP (1940), along with an excellent review of the history of sediment sampling. Shelley and Kirkpatrick (1973) describe over 70 commercially available and custom designed automatic samplers. The total number of models available today has been estimated to exceed 200 (Shelley; 1974). Not all of these are eminently suitable for suspended sediment sampling, however.

Following FIASP (1963), the designs can be grouped into the following six general types:

1. Ordinary vertical pipe,
2. Instantaneous vertical,
3. Instantaneous horizontal,
4. Bottle,
5. Pumping, and
6. Integrating.

The first type, although simple in design, has such adverse sampling characteristics that it is seldom used today by knowledgeable investigators. The unsuitability of both instantaneous types (and the bottle type to a lesser extent) can be best illustrated by recalling the earlier discussion of velocity fluctuations with time at a point in the cross section. Investigators have found that two minutes or longer is required at some points in order to obtain good average velocity data. Because of the dependence of sediment concentration upon velocity, a long sampling time is required to obtain a representative sample of sediment concentration. Based on extensive field data, FIASP (1963) recommends that a sampler be capable of sampling continuously for one minute. If such an instrument is not available, they state that, "not less than six 15-second samples and not less than three 30-second samples will probably be required to determine average concentration at a point".

The requirement for a piece of equipment to sample continuously for one minute and, as pointed out earlier, to have an intake velocity equal to the average stream velocity at the sampling point places some restrictions on the minimum sample size, apart from requirements for laboratory analysis. Considering an intake diameter of 0.63 cm and a stream velocity of 1 m/s, a one minute sample volume would be almost 2 liters. This has a direct impact on the type of sampler to be used

and, when combined with a requirement for unattended operation as might be the case when a number of samples are to be gathered at the same instant of time, strongly indicates consideration of pumping type designs.

In a pumping type sampler, the water-sediment mixture is sucked through an intake nozzle located at the sampling point. In a stream where the flow rate and direction are relatively constant, the intake is pointed into the current, and the pump speed is adjusted so that the intake velocity is approximately equal to that of the stream. When the flow direction is unknown, a vertical intake orientation is preferred. The sampler consists of the intake, pump, tubes or hoses for transporting the sample to the surface and depositing it into a container, and, in the case of automatic designs, a control and power subsystem. For complete descriptions of such components see, e.g., Shelley (1974). Pumping samplers, according to their design, can be used to obtain instantaneous or integrated samples at a point or at several points in the vertical simultaneously. Shelley (1976a) has designed a modular, multi-level intake sampler that can be used to gather either instantaneous or integrated samples at each intake point.

In laboratory tests of this prototype device involving a variety of suspended solids, Shelley (1976b) used a facility at LaSalle Hydraulic Laboratory Ltd which had the following capabilities; a test flume with a semi-circular invert (bottom), the ability to create stable flows over the velocity range of 0.3 to 2.4 m/s while maintaining a constant depth in the test section, an accurate means of determining flume discharge (i.e., flow velocity), a method for constantly adding suspended solids to the flow so as to create and maintain a known solids concentration in the flume, the ability to provide suitable synthetic solids representative of those encountered in storm and combined sewer flows, and the ability to provide laboratory analysis of samples taken during the testing program.

The facility used for the testing consisted of a water supply taken from a fixed pumping station in the laboratory, the flow channel or flume itself, a settling basin with a calibrated overflow weir, and an exit to a return channel to the pump. The flow channel was 12.2m long with a cross-section 0.3m wide by 0.6m deep, including a semicircular invert. A test section was provided 3.7m from the downstream end where a 2.54 cm recess in the wall was provided to allow routing the 1.6 cm O.D. tubes from the intakes of the prototype sampler to its pump box. This was done, in view of the channel width, to minimize any effects of these lines on the flow stream itself. Point gages upstream from the test section could measure the water level to ensure that depth control was maintained.

The normal water supply was taken directly from the pump. The flume and overflow weir were calibrated by a temporary supply which took its flow directly from one of the calibrated V-notch weir towers in the laboratory. The solids injection system consisted of a dry solids vibratory feeder with a plexiglass hopper fixed over it. The rate of vibration (and hence solids injection) could be controlled by a rheostat.

A wide range of suspended solids were used for creating the synthetic flows. They included:

a. Silica sand, specific gravity 2.65

fine - 120 mesh \underline{d} $\underline{\geq}$ 140 mesh (.105-.125 mm)

medium - 30 mesh \underline{d} $\underline{\geq}$ 35 mesh (.500-.595 mm)

coarse - 10 mesh \underline{d} $\underline{\geq}$ 12 mesh (1.68-2.00 mm)

b. Pumice, specific gravity 1.35

A single broad grain size distribution used in earlier storm and combined sewer flow synthesization was tested;

6 mesh \underline{d} $\underline{\geq}$ about 100 mesh (.149-3.36 mm)

- c. Gilsonite, specific gravity 1.06
 - fine - 12 mesh $\geq d \geq 30$ mesh (.595-1.68 mm)
 - medium - 10 mesh $\geq d \geq 12$ mesh (1.68-2.00 mm)
 - coarse - 6 mesh $\geq d \geq 8$ mesh (2.38-3.36 mm)

- d. Alathon, specific gravity 0.99
 - Uniform size of 3.0 mm

- e. Polythene, specific gravity 0.92
 - Uniform size of 4.0 mm

The initial phase of the controlled laboratory testing program involved using the prototype sampler over a wide range of test parameters (flow velocity, solids type and size, and concentration). The positions of the four sampling intakes used for the large majority of the testing are indicated in Figure 11. As can be noted, two were located near mid-depth while the other two were positioned near the water surface and near the invert respectively. This arrangement is essentially similar to the preferred three-point method of sampling discussed in FIASP (1963).

In addition to the prototype sampler, a so-called "reference" sampler was used in part of this testing phase. The reference sampler consisted of a "standard" sedimentation probe (provided through the courtesy of the Federal Inter-Agency Sedimentation Project Office at St. Anthony Falls) connected to a peristaltic pump with a variable speed drive arrangement. This reference sampler had been calibrated so that any desired sample intake velocity could be set in order to allow isokinetic sampling to be achieved. The intake probe could be positioned at any desired point in the cross-section of the flow with its inlet pointed directly upstream into the flow. The reference sampler was used primarily to investigate vertical and horizontal concentration profiles.

Note: Intake height above invert as a percent of total water depth as indicated in parenthesis.

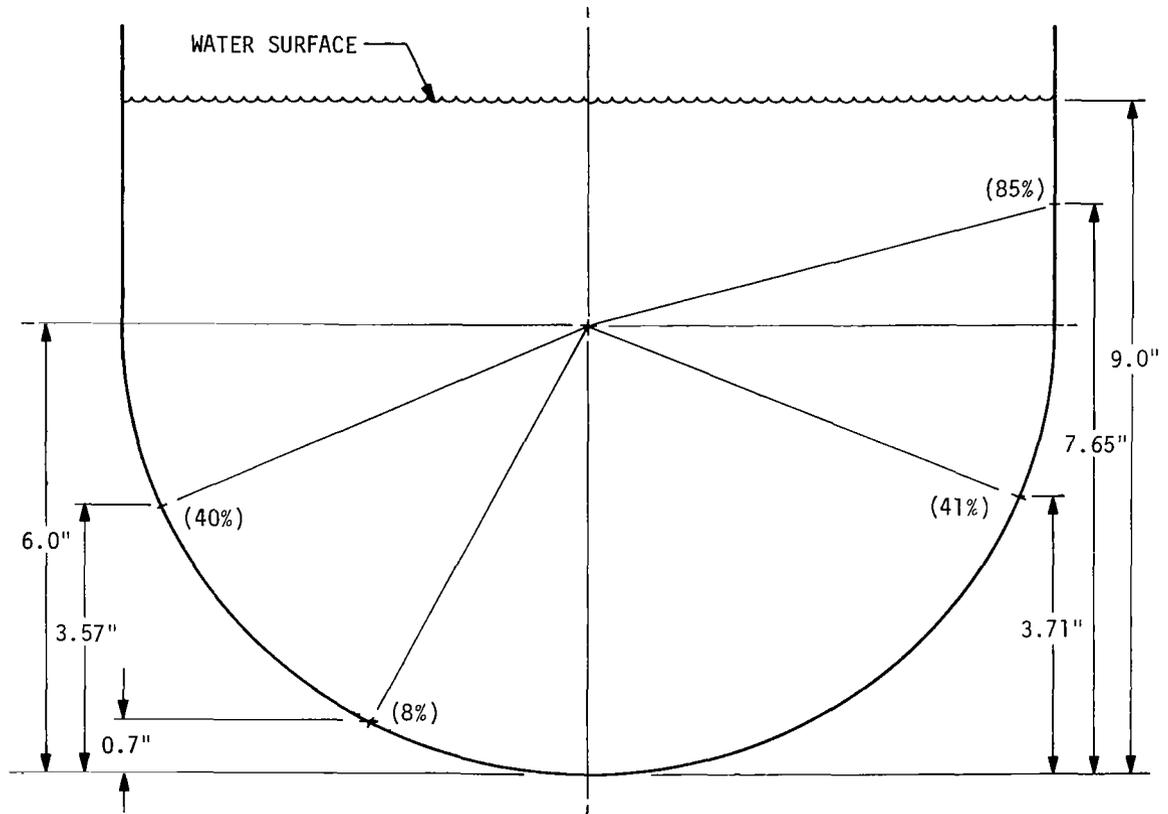


Figure 11. Intake Location of Prototype Sampler*

* Taken from Shelley (1976b).

Two results from the testing effort will be mentioned here. First, it is of interest to note the results of using this prototype device to gather samples of the relatively light (s.g. = 1.06) gilsonite when operating in an instantaneous mode. Four-second samples were gathered every thirty seconds for flume velocities of 0.6 and 1.2 m/s (2 and 4 fps) and typical results are presented in Figure 12. The range of total flume concentration (suspended solids plus bed load) is indicated by the shaded band. In an extended period of testing with gilsonite at various concentrations and flume velocities, it was found that the average of only five instantaneous samples would generally fall within the range of flume concentrations and typical deviations from flume averages were less than +10 percent.

The second result arises from another phase of the testing effort in which several of the more popular commercially available sampler designs were tested in a side-by-side fashion with the prototype. Although the testing was far from exhaustive, enough data were gathered to demonstrate that there can be marked differences in results obtained with different sampler designs, even under identical, controlled flow conditions. The performance of these commercial units ranged from overstatements of concentration by a factor of four to understatements by 70 percent or more. This is especially significant in view of the fact that a sampler of one of the designs used in this comparative testing effort was used by NASA in constructing an automated remote marshland water sampling station as reported by Thomas (1974). Based on the technical considerations of the sampling problem reviewed earlier and the testing results obtained, it does not appear reasonable to expect valid data from this station, at least insofar as suspended solids are concerned.

The integrating (either point or depth) sampler is the final type and, as used here, is a manually operated, gravity filled device. The newer models are designed to gather a sample from a vertical (not a point) in

MEDIUM GILSONITE

— 4 FPS

- - - 2 FPS

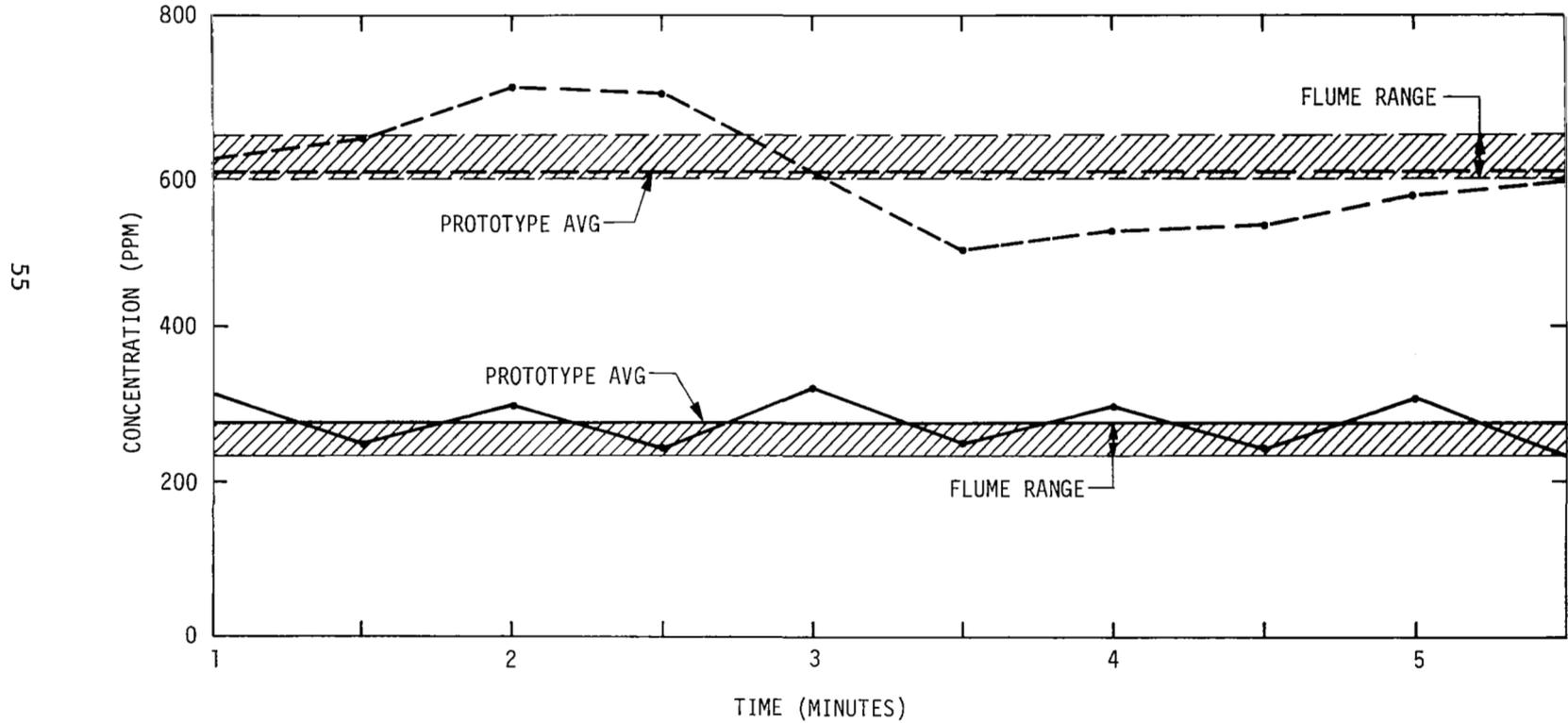


Figure 12. Variation of Gilsonite Concentration With Time*

* Taken from Shelley (1976b).

such a way that the velocity in the intake is approximately that of the stream. This is accomplished by valves and chambers that serve to equalize the pressure in the sample container with the external hydrostatic head at the intake at all depths. For a full description of these devices, their proper use, and a discussion of bed load samplers see, e.g., FIASP (1963) or the excellent summary by Guy and Norman (1970). One point must be made as regards the depth-integrating samplers, however. As they are designed, the nozzle cannot reach the lower 0.1m or so of the vertical. Therefore, the sediment obtained by the sampler in the sediment zone should be referred to as measured sediment discharge. This, when combined with the higher concentrations and coarser sizes of sediment passing beneath the nozzle in the unsampled zone, equals total discharge. These concepts are illustrated in Figure 13.

SEDIMENT ANALYSIS

Having collected a representative sample of the fluid mixture in question, there remains the problem of sample preservation and analysis. It is a practical impossibility either to perform instant analyses of the sample on the spot or to completely and unequivocally preserve it for subsequent examination. Preservative techniques can only retard the chemical and biological changes that inevitably continue following extraction of the sample from its parent source. In the former case, changes occur that are a function of the physical conditions - metal cations may precipitate as hydroxides or form complexes with other constituents; cations or anions may change valence states under certain reducing or oxidizing conditions; constituents may dissolve or volatilize with time, and so on. In the latter case, biological changes taking place may change the valence state of an element or radical; soluble constituents may be converted to organically bound materials in cell structures; cell lysis may result in release of cellular material into solution, etc.

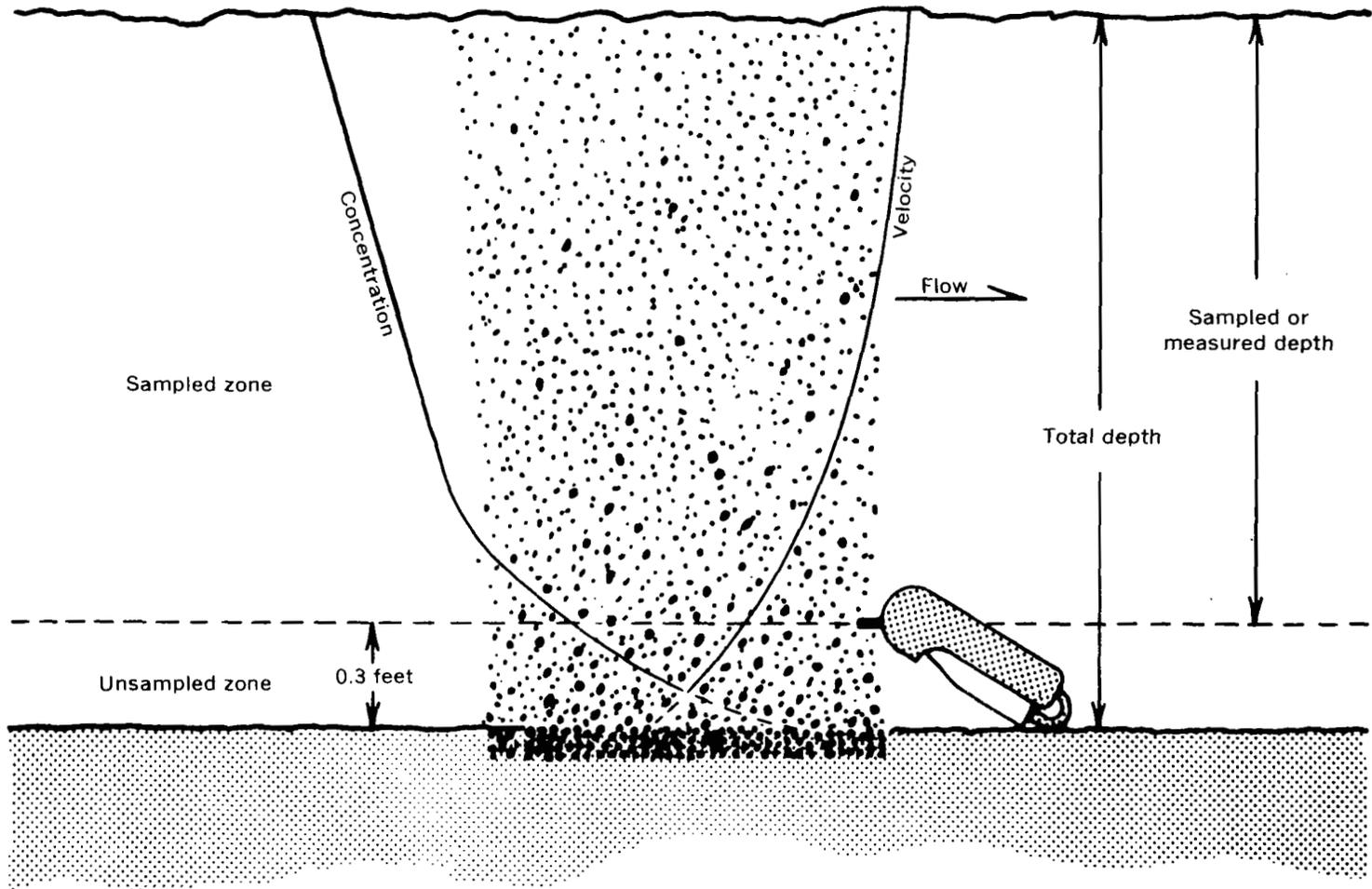


Figure 13. Depth-Integrating Sampler Concepts*

* Taken from Guy and Norman (1970).

Preservation methods are relatively limited and are generally intended to retard biological action, retard hydrolysis of chemical compounds and complexes, and reduce volatility of constituents. They are generally limited to pH control, chemical addition, refrigeration, and freezing. The Methods Development and Quality Assurance Research Laboratory (MDQARL) of the United States Environmental Protection Agency (1974) has compiled a list of recommendations for preservation of samples according to the measurement analysis to be performed. Since it is frequently of interest to examine a water-sediment sample for a number of parameters, this list has been reproduced here as Table 4.

Standard methods for the examination of water and wastewater have been set forth by the American Public Health Association (1971) and MDQARL (1974). As regards the solids content in particular, termed residue in these publications, methods are given for determining total residue (upon evaporation), total volatile and fixed residue, total suspended matter (nonfilterable residue), volatile and fixed suspended matter, dissolved matter (filterable residue), and settleable matter. These tests do not determine specific chemical substances, but classes of matter that have similar physical properties and similar responses to ignition. The tests are basically empirical in nature and, as a result, the constituents of each form of residue are defined to a large extent by the procedures employed. For this reason, close adherence to the established procedures is necessary to insure reproducibility and comparability of results. It is interesting to note that MDQARL (1974) states that precision and accuracy data are not available for methods used to determine total dissolved solids (total filterable residue), total suspended solids (total nonfilterable residue), total solids (residue), or settleable matter. The practical concentration range for the first three determinations is from 10 to 20,000 mg/l.

In comparison of results or data interpretation, it is important to recognize the fundamental differences in the results obtained using

TABLE 4. RECOMMENDATION PRESERVATION OF SAMPLES
ACCORDING TO MEASUREMENT⁽¹⁾

Measurement	Vol Req (ml)	Container	Preservative	Holding Time ⁽⁶⁾
Acidity	100	P,G ⁽²⁾	Cool, 4°C	24 Hrs
Alkalinity	100	P,G	Cool, 4°C	24 Hrs
Arsenic	100	P,G	HNO ₃ to pH <2	6 Mos
BOD	1000	P,G	Cool, 4°C	6 Hrs ⁽³⁾
Bromide	100	P,G	Cool, 4°C	24 Hrs
COD	50	P,G	H ₂ SO ₄ to pH <2	7 Days
Chloride	50	P,G	None Req	7 Days
Chlorine Req	50	P,G	Cool, 4°C	24 Hrs
Color	50	P,G	Cool, 4°C	24 Hrs
Cyanides	500	P,G	Cool, 4°C NaOH to pH 12	24 Hrs
Dissolved Oxygen				
Probe	300	G only	Det on site	No Holding
Winkler	300	G only	Fix on site	No Holding
Fluoride	300	P,G	Cool, 4°C	7 Days
Hardness	100	P,G	Cool, 4°C	7 Days
Iodide	100	P,G	Cool, 4°C	24 Hrs
MBAS	250	P,G	Cool, 4°C	24 Hrs
Metals				
Dissolved	200	P,G	Filter on site HNO ₃ to pH <2	6 Mos
Suspended			Filter on site	6 Mos
Total	100		HNO ₃ to pH <2	6 Mos

TABLE 4. RECOMMENDATION PRESERVATION OF SAMPLES
 ACCORDING TO MEASUREMENT⁽¹⁾ (Cont'd)

Measurement	Vol Req (ml)	Container	Preservative	Holding Time ⁽⁶⁾
Mercury				
Dissolved	100	P,G	Filter HNO ₃ to pH <2	38 Days (Glass) 13 Days (Hard Plastic)
Total	100	P,G	HNO ₃ to pH <2	38 Days (Glass) 13 Days (Hard Plastic)
Nitrogen				
Ammonia	400	P,G	Cool, 4°C H ₂ SO ₄ to pH <2	24 Hrs ⁽⁴⁾
Kjeldahl	500	P,G	Cool, 4°C H ₂ SO ₄ to pH <2	24 Hrs ⁽⁴⁾
Nitrate	100	P,G	Cool, 4°C H ₂ SO ₄ to pH <2	24 Hrs ⁽⁴⁾
Nitrite	50	P,G	Cool, 4°C	24 Hrs ⁽⁴⁾
NTA	50	P,G	Cool, 4°C	24 Hrs
Oil and Grease	1000	G only	Cool, 4°C H ₂ SO ₄ to pH <2	24 Hrs
Organic Carbon	25	P,G	Cool, 4°C H ₂ SO ₄ to pH <2	24 Hrs
pH	25	P,G	Cool, 4°C Det on site	6 Hrs ⁽³⁾
Phenolics	500	G only	Cool, 4°C H ₃ PO ₄ to pH <4 1.0g CuSO ₄ /l	24 Hrs
Phosphorus				
Orthophosphate, Dissolved	50	P,G	Filter on site Cool, 4°C	24 Hrs ⁽⁴⁾

TABLE 4. RECOMMENDATION PRESERVATION OF SAMPLES
 ACCORDING TO MEASUREMENT⁽¹⁾ (Cont'd)

Measurement	Vol Req (ml)	Container	Preservative	Holding Time ⁽⁶⁾
Hydrolyzable	50	P,G	Cool, 4°C H ₂ SO ₄ to pH <2	24 Hrs ⁽⁴⁾
Total	50	P,G	Cool, 4°C	24 Hrs ⁽⁴⁾
Total, Dissolved	50	P,G	Filter on site Cool, 4°C	24 Hrs ⁽⁴⁾
Residue				
Filterable	100	P,G	Cool, 4°C	7 Days
Nonfilterable	100	P,G	Cool, 4°C	7 Days
Total	100	P,G	Cool, 4°C	7 Days
Volatile	100	P,G	Cool, 4°C	7 Days
Settleable Matter	1000	P,G	None Req	24 Hrs
Selenium	50	P,G	HNO ₃ to pH <2	6 Mos
Silica	50	P only	Cool, 4°C	7 Days
Specific Conductance	100	P,G	Cool, 4°C	24 Hrs ⁽⁵⁾
Sulfate	50	P,G	Cool, 4°C	7 Days
Sulfide	50	P,G	2 ml zinc acetate	24 Hrs
Sulfite	50	P,G	Cool, 4°C	24 Hrs
Temperature	1000	P,G	Det on site	No Holding
Threshold Odor	200	G only	Cool, 4°C	24 Hrs
Turbidity	100	P,G	Cool, 4°C	7 Days

TABLE 4. RECOMMENDATION PRESERVATION OF SAMPLES
ACCORDING TO MEASUREMENT⁽¹⁾ (Cont'd)

NOTES:

1. Taken from MDQARL (1974).
2. Plastic or Glass.
3. If samples cannot be returned to the laboratory in less than 6 hours and holding time exceeds this limit, the final reported data should indicate the actual holding time.
4. Mercuric chloride may be used as an alternate preservative at a concentration of 40 mg/l, especially if a longer holding time is required. However, the use of mercuric chloride is discouraged whenever possible.
5. If the sample is stabilized by cooling, it should be warmed to 25°C for reading, or temperature correction made and results reported at 25°C.
6. It has been shown that samples properly preserved may be held for extended periods beyond the recommended holding time.

these different methods. For example, the test for settleable solids, which is usually a volumetric determination (ml/l), will give no information about material on a weight basis nor any indication as to the dissolved or floating solids or those of sufficiently small hydraulic size as to preclude their settling in a one hour time period. Total suspended solids determinations (expressed as mg/l) will include all solids regardless of density retained on a standard glass fiber filter after drying at 103-105°C, but will give no indication as to finer particulates or dissolved solids. These are all included in the determination of total solids. Thus, it is important to indicate (or determine) what method was used for the determination in order to avoid error or possible erroneous conclusions.

In addition to information as to the quantity and form of the matter in the sample, it is frequently desirable to perform a particle size analysis. A brief review of methods often used is given by FIASP (1964) and is abstracted in the following descriptions.

In size analysis by sieving, particles are allowed to fall as far as they will through a nest of sieves that have coarse openings at the top and successively smaller openings toward the bottom. Results of an analysis may be expressed in percentage coarser (retained on or above) than each successive sieve size. Materials may be sieved wet or dry. Sieves are agitated mechanically or by hand. Changes in duration or method of sieving and wide variations in openings in sieves of the same nominal size make sieving inexact, especially for particles of irregular shapes.

In the visual-accumulation tube method the particles fall from a common level in a sedimentation tube filled with water. The particles form a stratified sedimentation system as they fall. The accumulation of sediment at the bottom of the tube is recorded against time of fall. The method is a fast, economical, and accurate means of determining the fall-velocity size distribution of sands.

In the bottom-withdrawal tube method of size analysis, particles fall from an initially dispersed suspension of particles in water. Several withdrawals of water and deposited sediment are made from the bottom of the sedimentation tube at timed intervals. The sediment is dried and weighed, and the size distribution is determined by the Oden curve procedure. The method is accurate for samples of silt and clay sizes. A single analysis of a sample containing sands is likely to be erratic.

In the pipette method the sediment is dispersed thoroughly in water in a cylinder and then allowed to settle. After a definite settling time a small sample is withdrawn at a fixed point below the water surface. The depth and time give fall velocity, which determines the maximum sediment size at the point of withdrawal. From several withdrawals that represent different particle sizes, the concentration of sediment finer than these selected sizes can be obtained.

The sedimentation principles in hydrometer analysis are the same as those in pipette analysis. However, concentration of sediment is determined from a hydrometer reading of the density of the water-sediment mixture at the reference depth and time. Because concentration determination with the hydrometer is not very sensitive, sediment is usually analyzed in too great a concentration for unhindered settling of the sediment particles. The hydrometer method is used mainly in analysis of soils.

Centrifuge methods of size analysis are sedimentation methods in which a centrifuge is used to hasten particle settling. They are especially valuable for analysis of fine silt and clay.

Sediment particles may be magnified with a microscope so that their size may be determined. In general, microscopic size is determined from measurement of length along two axes of the particle, and the depth of the particle is estimated or assumed in relation to the measured dimensions. For spherical particles the microscopic method is

accurate within the limitations of the available microscope. An analysis requires measurement of at least a few hundred particles. Thousands of particles must be measured to obtain an accurate size distribution for a sample containing a wide size distribution of irregular particle shapes. Microscopic size analysis is tedious and expensive but provides a dependable standard by which to judge the accuracy of other size analysis methods.

The electronic counter is well adapted to analysis of sediment particles from 1 to 160 microns in size, if apertures from 50 to 400 microns in diameter are used. Apertures up to 2,000 microns are available but the problem of keeping sediment particles larger than 160 microns in suspension makes other methods such as the visual-accumulation tube or sieve methods more desirable for larger particles. Apertures as small as 11 microns are available, but an analysis with so small an aperture requires additional time and the prior removal of all but the clay particles. In operation a known volume is metered from a dilute suspension in which the sediment particles are uniformly dispersed. As the individual particles pass through a small aperture they produce an electrical pulse that is proportional to particle volume. The numbers of pulses larger than several successive reference sizes are counted. By calibration the electrical-pulse sizes are related to particle sizes. The size distribution and concentration can then be determined.

A comparison of these various particle size analysis methods is presented in Table 5. Although the cost data are over ten years old, and hence, no longer should be used in an absolute sense, they are of value in a comparative sense.

Turbidity is another property of water samples relating to their suspended solids content that is frequently determined. It is caused by the presence of such suspended matter as silt, clay, finely divided organic matter, and plankton and other microscopic organisms. It is

TABLE 5. COMPARISON OF SIZE ANALYSIS METHODS⁽⁶⁾

Method	Average Time Per Analysis ⁽¹⁾	Size Range (Microns)	Concentration Minimum (ppm) ⁽²⁾	Estimated Accuracy ⁽³⁾	Cost
Counter	8 hours	1-160	Unlimited ⁽⁴⁾	±10%	\$30
Sieve	1 hour	44-up	500	±25%	4
Visual accumulation tube	1/3 hour	62-1000	200	±10%	2
Bottom-withdrawal tube	4 hours	2-100	300	±40%	15
Pipette	1 hour	1-62	1,000	±20%	4
Hydrometer	1/2 hour	1-62	10,000 ⁽⁵⁾	±40%	2
Centrifuge	3/4 hour	1-62	200	±20%	4
Microscope	8 hours or more	1-up	Unlimited ⁽⁴⁾	±10%	30 and up
Electron microscope	30 hours or more	.05-70	Unlimited ⁽⁴⁾	±10%	100 and up

- 1) Does not include sample preparation, and assumes several samples are run routinely.
- 2) In a one-pint sample.
- 3) Of median diameter at 95% confidence level.
- 4) Unlimited as long as sample represents the original size distribution.
- 5) Extremely variable but generally high.
- 6) Taken from FIASP (1964).

important to understand that turbidity is an expression of the optical property of a sample which causes light to be scattered and absorbed rather than transmitted in straight lines through the sample. The standard method for measurement based upon the Jackson candle turbidimeter measures the distance of the light path through a suspension which just causes the image of the flame of a standard candle to disappear. This distance is inversely related to Jackson Turbidity Units (JTU), the measure of the light transmissibility of the fluid, i.e., the residual light not deflected by particulate material is measured. A light path of 72.9 cm corresponds to 25 JTU, the lower threshold of the method, and a 2.3 cm path corresponds to 1000 JTU, the recommended upper limit of the method.

Alternatively, nephelometric methods measure the intensity of the light which is scattered by the sample (usually at 90° to the incident beam). The theory of light scattering from particles with known properties is well developed but complex. In the case of uniform particles which are small compared to the wavelength of light, a measure of sample turbidity can be expressed as

$$R = KCd^3 \left(\frac{n^2 - m^2}{n^2 + 2m^2} \right) \frac{m^4}{\lambda^4} \quad (11)$$

where R is the ratio of the intensity of light scattered at 90° to that of the incident beam, K is a constant, C is the volumetric concentration of the sample (ml/l), d is the diameter of the solid particles, n is the refractive index of the particles, m is the refractive index of the solvent, and λ is the wavelength of light used. In the more practical case where there is a range of particle sizes, shapes, and refractive indices, empirical correlations are used. In nephelometry, the turbidity of a particular concentration of formazin suspension is defined as 40 units, and this standard reference suspension is used as a comparative base. MDQARL (1974) notes that nephelometric turbidity units (NTU)

"are considered comparable to the previously reported Formazin Turbidity Units (FTU) and Jackson Turbidity Units (JTU)", but this is an empirically observed comparability rather than a universal truth.

The normal range of nephelometric measurement is from 0 to 40 units, and samples of higher concentration are to be diluted to within 30-40 units before measurements are taken. Although most nephelometers are capable of reading suspensions with much higher turbidities than 40 units, the American Public Health Association (1971) notes that, "High turbidities determined by direct measurement are likely to differ appreciably from those determined by the dilution technique." They also note that even within the 0-40 unit range, "Differences in physical designs of turbidimeters will cause differences in measured values for turbidity even though the same suspension is used for calibration." Table 6 provides recommendations on reporting turbidity readings for both a candle turbidimeter and a nephelometer. The turbidity of a quiescent suspension in a sample tube may be quite different from that of the parent source where turbulent flow characteristics would tend to maintain heavier particles in suspension. This fact also helps explain differences in readings taken in situ by continuous flow nephelometers from other types of turbidity measurements.

Transparency is another term without strict definition that is used to indicate the optical character of water. It also is dependent upon the nature and amount of suspended matter and light-absorbing substances. Transparency is roughly measured by the use of a Secchi disk, a circular white disk usually between 43 and 237 cm in diameter. The disk is lowered into the water and the depth at which it is no longer distinguishable from the background is noted. In shallow water, light reflected from the bottom may cause difficulties, since one is actually observing the disk brightness as contrasted to the brightness of the surrounding water. Limited attempts to correlate Secchi disk readings with those of a turbidimeter have been made, but success in obtaining a general relationship remains to be demonstrated.

TABLE 6. RECOMMENDATIONS ON REPORTING TURBIDITY READINGS*

Turbidity Range Units	Candle Turbidimeter Record to Nearest:	Nephelometer Record to Nearest:
0 - 1.0	0.1	0.05
1 - 10	1	0.1
10 - 40	5	1
40 - 100	5	5
100 - 400	10	10
400 - 700	50	50
700 - 1000	100	50
>1000	100	100

* Recommendations taken from American Public Health Association (1971).

In closing this brief discussion of sediment analysis, the role of the analytical laboratory must not be underestimated. To be of value, the data it provides must correctly describe the characteristic or concentration of the constituents of interest in the sample submitted to it. In many cases, an approximate answer or incorrect result is worse than no answer at all, since it could lead to faulty interpretations and incorrect decisions. MDQARL (1972) has prepared a handbook for analytical quality control that provides sufficient information to allow inauguration or reinforcement of a program which will emphasize early recognition, prevention, and correction of factors leading to breakdowns in the velocity of data products from water and wastewater laboratories.

SECTION IV INDIRECT MEASUREMENT OF SEDIMENT

As is apparent from the foregoing discussion, the direct measurement of sediment in larger bodies of water, such as in estuarine and coastal areas, can be an involved and expensive task. For some areas it is not inconceivable that the costs of a comprehensive direct sediment measurement program, maintained over time for continual input to the management process, could approach the order of magnitude of the costs associated with the mitigation, amelioration, and alternative-measure systems used for the alleviation, preservation, or enhancement of environmental quality. Fortunately, such detailed data are not normally necessary, and synoptic data products are generally useful for decision making in a resource constrained setting, provided they can be properly understood and interpreted. Recent developments in remote sensing technology appear to offer a viable method for the indirect measurement of suspended sediment. However, two criteria must be established in order to estimate the utility of such techniques; their analytical capabilities and their economic competitiveness. Until the former is established, the later cannot be meaningfully addressed. Therefore, we will examine it in the light of current capabilities.

A THEORETICAL CONSIDERATION

We begin with two fundamental assumptions, namely: (1) all matter, on the earth's surface and within its waters, to some extent continuously radiates or reflects electromagnetic energy; and (2) spectrally selective emission and reflection can be used as a means of distinguishing types or states of matter, with spectral signatures serving as a leading means of interpretation. The remote sensor of interest here will, in some fashion, measure and record this electromagnetic energy. Data processing techniques ranging from visual interpretation to computer

algorithms may be used to make determinations. For the moment we shall not concern ourselves with the remote sensing platforms employed, except to note that either aircraft or satellites may be used as appropriate.

The variables that affect the energy flow of interest here are schematically diagrammed in Figure 14. In terms of the radiance spectrum at the position of the sensor $R(\lambda)$, we may write

$$R(\lambda) = R_s(\lambda) + \alpha(\lambda)R_{ss}(\lambda) + \beta(\lambda)R_v(\lambda) + \delta(\lambda)R_b(\lambda) \quad (12)$$

where $R_s(\lambda)$ is the radiance spectrum (at the sensor) of all the energy that is scattered back to the sensor without striking the water surface; $R_{ss}(\lambda)$ is the radiance spectrum contribution at the surface attributable to reflection from the water surface proper; $R_v(\lambda)$ and $R_b(\lambda)$ are the diffuse radiance spectra just above the water surface that are due to photons that have penetrated the water and are reflected either by the water volume proper or the bottom, respectively; and $\alpha(\lambda)$, $\beta(\lambda)$, and $\delta(\lambda)$ are atmospheric transmittance factors that are not necessarily equal because the radiance distributions of $R_{ss}(\lambda)$, $R_v(\lambda)$, and $R_b(\lambda)$ are different. Of course, it is possible for photons to be reflected from the water surface, backscattered from the atmosphere into the water, and scattered back into the atmosphere after having interacted with the water volume, bottom, or both. Photons that do this are considered to be a part of $R_v(\lambda)$ or $R_b(\lambda)$ respectively.

The radiance $R_s(\lambda)$ at the sensor is completely indifferent to any properties of the surface. The upwelling radiance above the water due to specular reflection from the surface and diffuse reflection from white caps, foam, and bubbles on or just beneath the water surface, $R_{ss}(\lambda)$, also contains no information about the conditions beneath the water surface. The radiance $R_b(\lambda)$ contains information about the optical character of the water volume combined with the reflective characteristics of the bottom. Thus, as presented in equation (12), only $R_v(\lambda)$

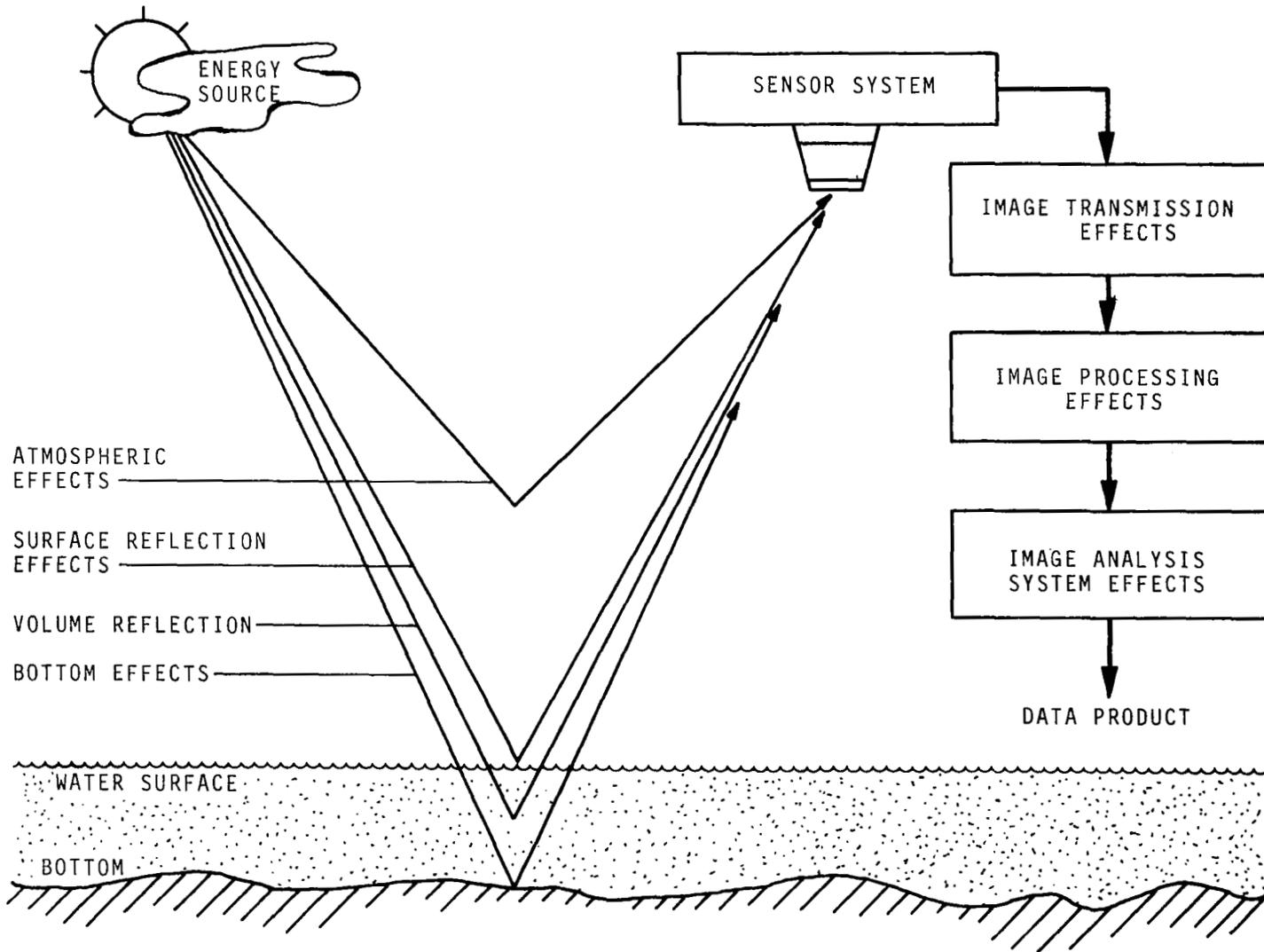


Figure 14. Energy Flow and System Variables That Affect the Final Data Product

solely contains information about conditions beneath the water surface such as the composition and concentration of suspended and dissolved matter. Some understanding of the dependence of $R_v(\lambda)$ on the basic optical properties of the water and its constituents is therefore required in order to obtain quantitative information about these constituents from measurements of $R_v(\lambda)$.

As noted in Figure 14, other factors to the final data product are sensor system effects (geometric, photometric, and mechanical and electrical operating characteristics), possible image transmission effects, image processing effects (e.g., film sensitivity, processing, and handling) and, finally, image analysis system effects (including training errors). The point of all this is that any characteristics of the data product (such as density variations recorded on film) that are in response to any factor or combination of factors other than volume reflectance, $R_v(\lambda)$, must not be interpreted as a manifestation of changes in water quality.

SOME EXPERIENCE WITH REMOTE SENSOR MEASUREMENTS

The realization that the presence of suspended solids in water could be detected in photographic images taken from a remote sensor platform such as an airplane is not new, and the efficiency of this way of examining the problem in estuarine and coastal areas has long been recognized in view of the requirement to examine water masses over broad (and relatively inaccessible) areas, and to do this with some continuity over an extended time period. The early data products were often simply "pretty pictures," however, and gave only limited, qualitative information. Fortunately, improvements in sensors and image processing and analysis systems allow us to do much more today. Some selected recent experiences will be used as examples.

In his study of the dynamics of playa lakes in the Texas high plains, Reeves (1973) found that color composites using an electronic density profile, portrayed gradations in water transparency due to depth fluctuations, suspended solids, or algae much better than the single multispectral scanner (MSS) bands used on the Earth Resources Technology Satellite (ERTS-1).^{*} Lind (1973) reported that ERTS-1 provided pollution plume data which were accepted as evidence on 4 October 1973 in a Supreme Court case involving the States of Vermont and New York and a major paper company. This marked the first time that satellite imagery and information derived therefrom had been so used in a court of law. Three ERTS-1 scenes revealed the extent of the papermill effluent associated with a submerged diffuser pipe extending from the mill's wastewater treatment plant. Although MSS band 4 proved to be the most useful single band for study of the plume area, a multispectral combination of MSS bands 4, 5, and 6 was used to emphasize plume patterns further. Lind (1973) also reports considerable success in observing turbidity patterns, including indications of the rate of shore erosion at tracts where emergent lacustrine silts and clays come under wave attack.

Based upon multispectral high altitude (18 km) photography, Pluhowski (1973) reports much success in defining turbidity plume dynamics of large and medium size rivers entering Lake Ontario. Plume configurations were well defined and lake circulation easily identified for the most part. The existence of erosive littoral currents generated by strong onshore winds that subtend a large angle with a line normal to the lake's coastline was readily determined from the photographs. The plume from a submerged sewer outfall located in Lake Ontario near the City of Rochester, NY was also easily discernable.

Polcyn and Lyzenga (1973) report a multispectral ratio technique that was used to prepare a depth chart down to 10m for the Little Barbara Bank. The technique makes use of the different water penetration characteristics of colors in the blue-green and the red wavelengths,

^{*} now Landsat 1

and has obvious implications in the overall study of sedimentation and erosion processes. They also report distinguishing high turbidity linear features, extending for several kilometers due to currents, that were attributed to fish action producing high sand suspension.

In studies of sediment concentration mapping in tidal estuaries, Williamson and Grabau (1973) developed an analytic procedure that, in essence, considers the ERTS-1 MSS as a reflectance spectrophotometer that senses and records the spectral reflectance (and emittance if any) of a scene on a pixel-by-pixel basis. A pixel (or picture element) here is the area over which radiant power is integrated and measured. By placing the values for a pixel in each MSS band into juxtaposition, a crude reflectance spectrum for the corresponding ground area can be defined. Only limited computer capability is required to search the data defining the spectral reflectance characteristics of a scene on a pixel-by-pixel basis, identify each pixel whose spectral reflectance matches a reference spectrum, and generate maps that identify pixel locations where spectrum matches occur and the spectrum that was matched. In the event that the reference spectra uniquely represent a specific condition on the ground, the result is a map of the distribution of that condition. This procedure was demonstrated by the mapping of sediment distribution by concentration level (0-10, 10-20, 20-30, and over 30 mg/l) in four estuaries around the Chesapeake Bay. The spectral signatures of the suspended materials were not as distinct as had been hoped for, and considerable subjective judgement was required to establish reference spectra. Other difficulties arose from the inability to accurately fix the location on the surface of a single pixel (average error ~ 100m implying an uncertainty within 9 pixels).

As a part of an ongoing study of coastal water monitoring, Klemas, et al., (1973) reported on ERTS-1 data comparisons with ground truth data collected from helicopter and boat transects (including Secchi depth, suspended sediment concentration and size, transmissivity,

temperature, salinity, and water color). A number of U-2 and C-130 overflights took place during the same time period, and small aircraft equipped with clusters of filtered film cameras were used to underfly each ERTS-1 overpass. The results of extensive earlier ground truth investigations can be summarized as follows:

- Concentration of suspended sediments in the Delaware Bay averaged 30 mg/l; during July-August the average was 18 mg/l.
- Concentration gradients of suspended sediments were greater during ebb than flood due to greater turbulence and better mixing during the latter stage.
- Turbidity increased with depth except during periods of bloom, when surface turbidities sometimes approached or exceeded those at greater depths.
- Turbidity decreased from winter to summer, but marked increases were observed during May and September due mainly to plankton blooms.
- Suspended sediments were mostly silt-clay sized particles with mean diameters around 1.5 microns; the predominant clay minerals are chlorite, illite, and kaolinite.
- Reflectivities for Delaware Bay sediments were measured to be around 10%.

Typical Secchi depth readings ranged from around 0.2m near the shore to 2m in the deep channel, and "equivalent" measurements with green and red boards did not exceed those obtained with the white disc. Therefore it was concluded that it is quite unlikely that the bottom would be

visible in any of the ERTS-1 channels and that most of the visible features in the Delaware Bay would be caused by light reflected off the surface or backscattered from suspended matter.

ERTS-1 band 5 was found to be the most sensitive to suspended sediment features, but even here the sediment patterns were revealed by only four to five neighboring shades of grey in the negative transparencies and about twice that number in the digital tapes. However, pollution plumes from a barge disposing acid wastes were more strongly visible in MSS band 4 images. It was concluded that image radiances (microdensitometer traces) correlated well with Secchi depths and suspended sediment concentrations taken at the surface and at a depth of 1m, with band 5 giving the best representation of sediment load within that portion of the water column. Color density slicing of all four MSS bands gave an indication of relative sediment concentration as a function of depth, since the four bands penetrate to different depths ranging from several meters to several centimeters, respectively. Circulation patterns observed by ERTS-1 during different parts of the tidal cycle agreed well with measured and predicted currents throughout the Delaware Bay.

In a related study of coastal zone classification from satellite imagery, Klemas, et al. (1975) reported on results of using ERTS-1 MSS data and SKYLAB-EREP photographs in an attempt to inventory and monitor significant natural and man-made cover types in Delaware's coastal zone. Automatic classification of ERTS data yielded classification accuracies of over 80 percent for all 15 training categories tested, while visual interpretation of EREP Earth Terrain photographs distinguished a minimum of ten categories with classification accuracies ranging from 75 to 99 percent. Two of these categories were deep saline water and sediment laden and shallow saline water.

Pirie (1973) reports on a California coastal processes study whose objectives are to analyze nearshore currents, sediment transport, and estuarine and river discharges. Major conclusions drawn from ERTS-1 imagery were:

- Distinct seasonal patterns for sediment transport as a function of the oceanic current systems and coastal morphology were identified.
- Large-scale sediment plumes from intermittent streams and rivers extend offshore to previously unanticipated ranges. Furthermore, areas where these plumes contain possible contamination from onshore activities can be traced in detail.
- Automated contouring of radiance levels can be used to generate charts for determination of surface and near-surface suspended sediment distribution.

It was noted that in situ measurements of suspended sediment as a function of depth in the water column and lateral extent showed a very complex, three-dimensional development, with such sediment clouds having either sharp or diffuse boundaries at intermediate depths resulting in reflection (or back scattering) of a disproportionate amount of light. This creates difficulties in sediment load determination from film densities. Data were presented (reproduced here as Figure 15) showing that normalized transmittance is primarily due to the scatter type (i.e., in the lagoon, the surf zone, or the ocean) and only to a much lesser extent due to the specific sediment load (note curves M-3 and M-5 of Figure 15 in particular). On the other hand, Secchi disc readings in extremely turbid San Francisco Bay waters showed a strong correlation of sediment loads with 450 nm band film density readings (all data were under 50 mg/l).

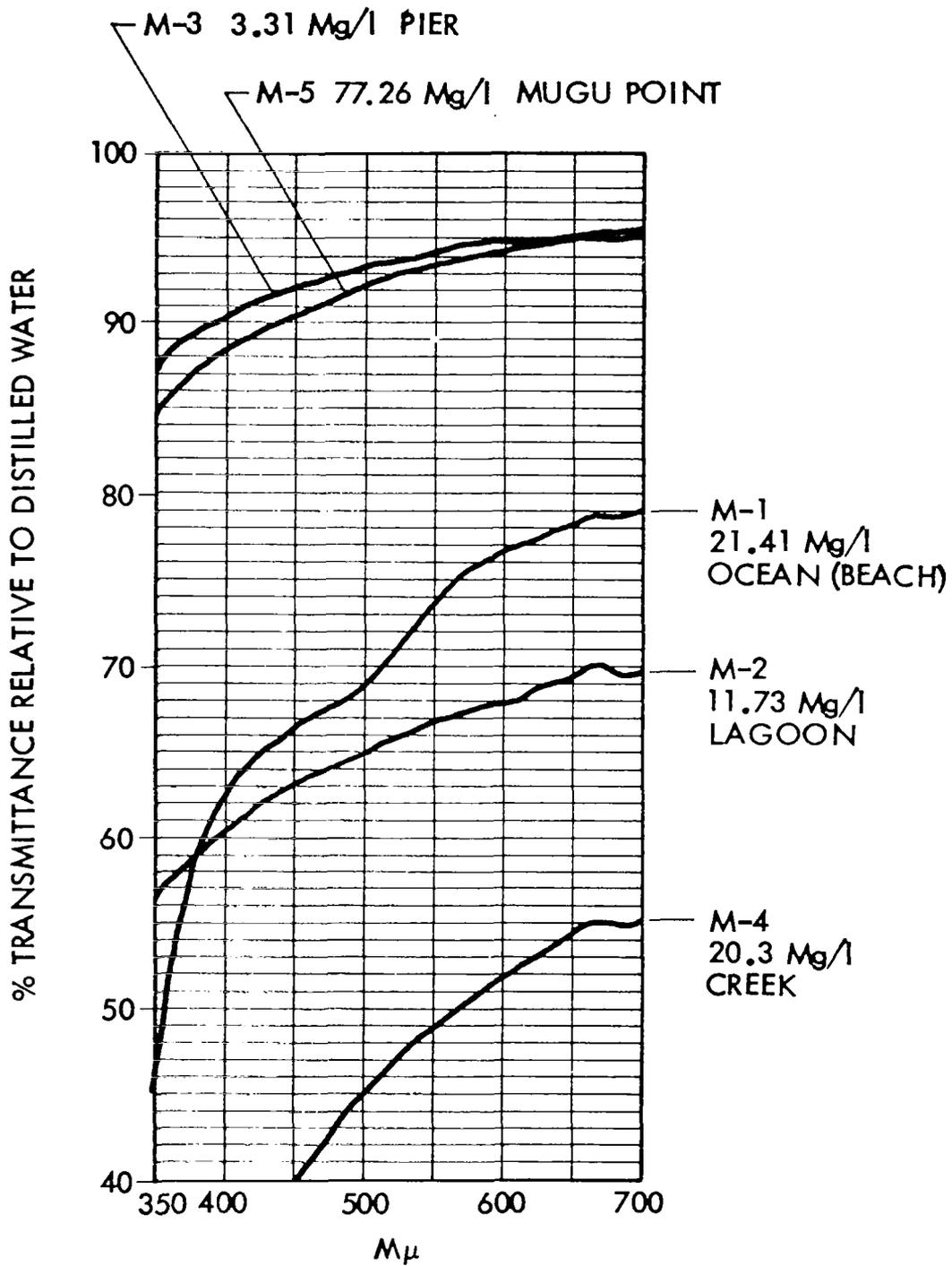


Figure 15. Mugu Lagoon and Ocean Water Sediment Loads and Spectral Transmittance*

* Taken from Pirie (1973).

Yost, et al. (1973) used additive color viewing and electronic image analysis to make water characteristic determinations from ERTS-1 photographic data products of the New York Bight. It is reported that prediction of the absolute value of total suspended particles can be made using composites of positives of MSS bands 5 and 6 which were precisely made using the step wedge supplied on the imagery. These were on a total particles per liter basis as opposed to either a volumetric or gravimetric basis. It was also found that predictions of the relative value of the extinction coefficient could be made using bands 4 and 5.

Scherz, et al. (1973) report on extensive laboratory analyses of water samples taken from Lake Superior (total solids, volatile solids, suspended solids, dissolved solids, turbidity, color, and volume reflectance and transmittance at different wavelengths). Volume reflectance was found to correlate well with both Secchi disc readings and turbidity measurements for all samples. Suspended solids concentration could only be correlated well with turbidity for data taken within a relatively short time frame (on the same day). This is due to the changes of the character of the suspended solids (e.g., size, shape, composition). Thus, the correlation, although good for any given day, was found to change from day to day. For example, a turbidity reading of around 15 JTU corresponded to a concentration of 10 mg/l on one day, whereas it had corresponded to over twice that amount only six days earlier. These data were compared with low altitude (under 300m) aerial photographs. The reflectance obtained from the photographs for a given day also correlated fairly well with turbidity in general and with suspended solids concentrations for each particular day. The correlation was found to be of the same form as that of the laboratory data but shifted considerably (e.g., the straight line on a log-log plot of the photo data was much higher and had nearly twice the slope as compared to that of the laboratory data). This is because the laboratory measurement was true volume reflectance, whereas the photographic

data also contained surface, skylight, and atmospheric effects which were variable from day to day. Similar results were obtained with ERTS-1 imagery. It was also pointed out that proper use of remotely sensed data such as these images would have avoided an \$8M blunder in the location of a drinking water intake in the portion of Lake Superior under study.

In a study attempting to quantify water quality using ERTS-1 imagery, Yarger, et al. (1973) report on specific results for two major reservoirs in Kansas. Approximately ten water samples were collected from each reservoir during each cloud-free ERTS-1 overpass and were analyzed for concentrations of inorganic suspended and dissolved solids, organic suspended and dissolved solids, chlorophyll, potassium, phosphate and nitrate ions. Secchi disc and temperature measurements were also made at each sampling site. The effect of sun angle on reflectance levels from a concrete dam at one of the reservoirs (Tuttle Creek) was investigated in terms of the average digital level on the computer compatible tapes (CCT) of the MSS bands. A strong dependency was found for all bands (see Figure 16a), but could be suppressed by forming band ratios as typified by Figure 16b. There is also a sun angle effect for water reflectance levels (decreasing with lower sun angles as shown for MSS band 5 in Figure 17a) and also for correlation (slope) between reflectance level and suspended solids concentration (at least in the 0-90 ppm range). On the other hand, the magnitude of MSS5/MSS4 ratios are virtually indistinguishable for the same three sun angle passes as can be seen in Figure 17b, but the slopes remain rather flat.

Correlations with ground truth were accomplished by extracting digital levels from the CCT for the 9 pixels centered around the coordinate of the sampling station (amounting to a square area 240m on a side) and averaging them. All regression analyses were performed with ground truth as the dependent variable and MSS data as the independent variable. MSS5/MSS4 was found to have a roughly linear correlation in the 0 to

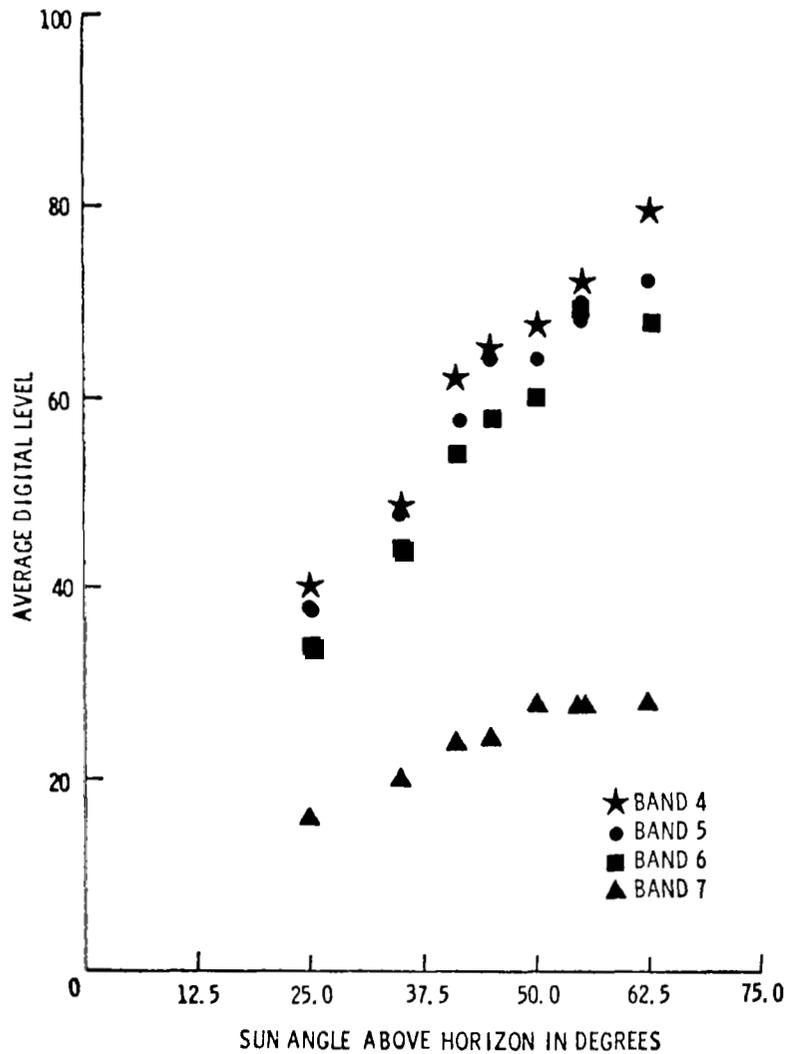


Figure 16a. MSS Digital Levels from CCT Vs. Sun Angle for Tuttle Creek Concrete Dam*

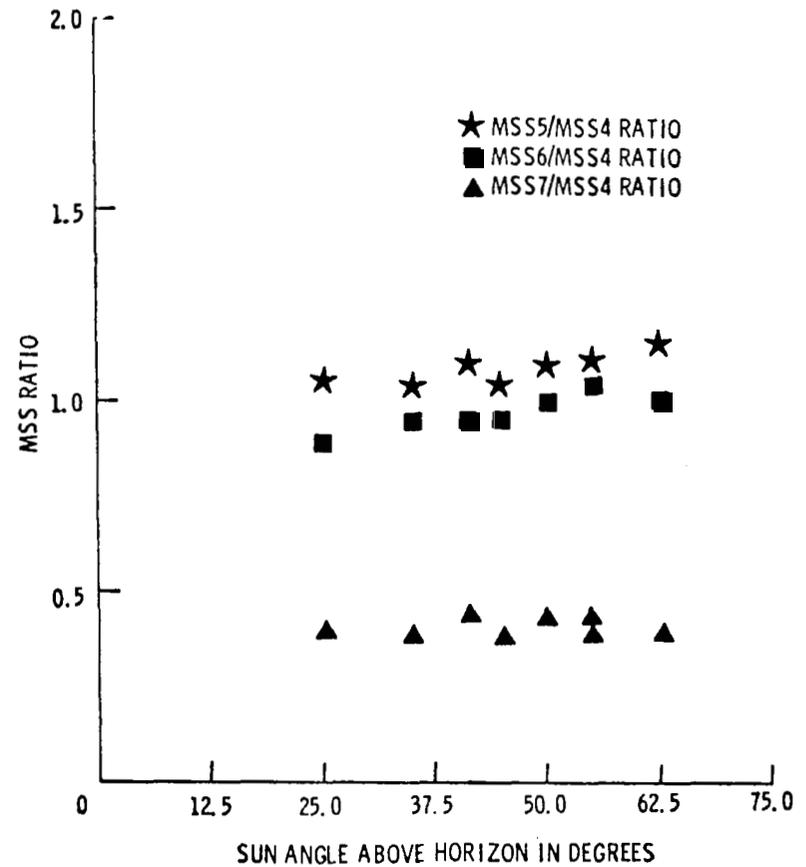


Figure 16b. MSS Band Ratios from CCT Vs. Sun Angle for Tuttle Creek Concrete Dam*

* Taken from Yarger, et al. (1973).

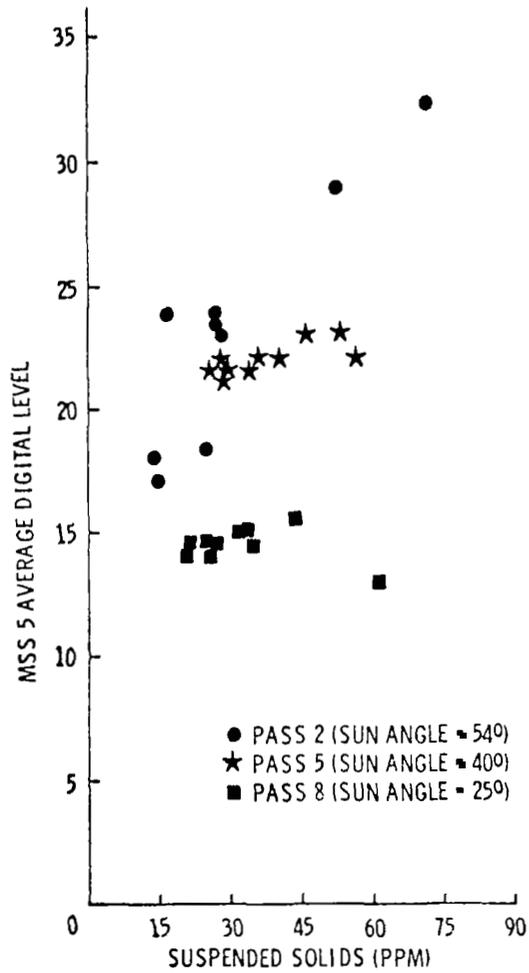


Figure 17a. MSS5 Digital Levels from CCT Vs. Suspended Solids for 28 Water Samples from 3 ERTS-1 Passes*

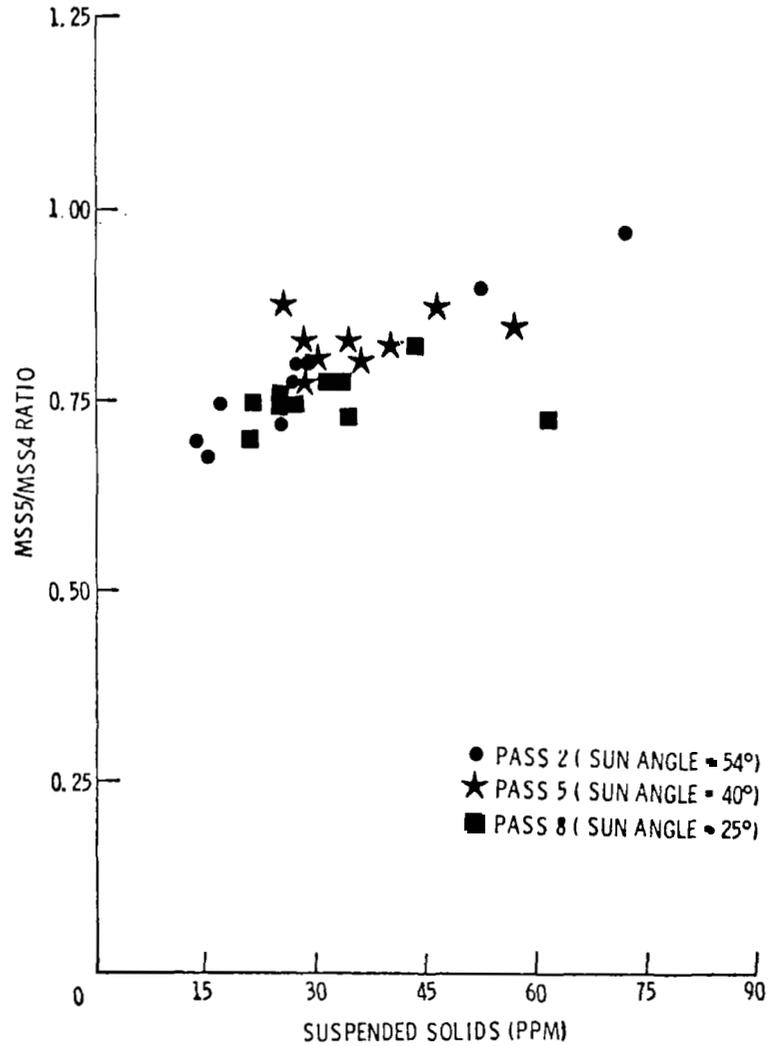


Figure 17b. MSS5/MSS4 Ratio from CCT Vs. Suspended Solids for 28 Water Samples from 3 ERTS-1 Passes*

* Taken from Yarger, et.al. (1973).

80 ppm range with a RMS residual of 12 ppm. MSS6/MSS4 yielded a smoothly varying polynomial fit over a 0 to 900 ppm range with a RMS residual of 31 ppm. In the 0 to 100 ppm range, the correlation was linear with a RMS residual of 13 ppm. The MSS7/MSS4 correlation was somewhat weaker over the 0 to 900 ppm range, with approximately a 50 ppm accuracy level.

Klooster and Scherz (1974) report on an aerial reconnaissance technique for correlating water quality parameters to aerial photographs. They found a positive correlation between reflectance and turbidity that was permanent for any particular waste. At certain times, other parameters such as suspended solids correlate to turbidity and may be mapped. They found that proper analysis of aerial photographs to determine water reflectance requires a standard reflectance panel somewhere in the frame. Noise in the analysis is due to bottom effects, reflection from the air-water interface, and path luminance; all of which may be dealt with, to some extent, by proper techniques.

Lillesand, et al. (1975) report on a method developed to quantitatively delineate waste concentrations throughout waste effluent mixing zones on the basis of densitometric measurements extracted from aerial photographs. It is pointed out that the following requirements must be accounted for if photo-image density measurements are to be used to quantitatively estimate water quality throughout the mixing zone:

1. a systematic relationship between water-sample reflectance and some measure of water quality (suspended solids, turbidity, etc.);
2. a proper accounting for the relationship between film exposure and scene reflectance; and

3. an adequate approximation of the relationship between film density and film exposure.

If these are met, measured image densities can be used to find film exposure levels; film exposure levels can be used to find scene reflectance levels; and scene reflectance levels can be used to quantitatively estimate water quality parameter values. Arguments are given for the development of a model for the estimation of suspended solids S , from measured film density $D(\lambda)$, in the form

$$S = \alpha(\lambda) 10^{Z(\lambda)D(\lambda)} + \beta(\lambda) \quad (13)$$

where $\alpha(\lambda)$ and $\beta(\lambda)$ are model parameters and $Z(\lambda)$ is the log exposure. Details of the application of this model to a field study of a paper mill effluent plume are given, and a map of the plume by suspended solids concentration level (from 20 to 70 mg/l in 10 mg/l steps) so derived is presented. It was observed that "an adequacy of fit test performed on each model solution showed variations between observed and modeled concentrations to be attributable to the experimental error inherent in collecting and processing the suspended solids ground truth."

Pionke and Blanchard (1975) review some recent investigations of suspended sediment measurement by remote sensing and report on their own work in this area related to small impoundments. They observe that although turbidity is related to reflectance, the form and limits of the relationships, sensitivity of response, and shifts or changes in the relationship due to characteristically different suspended sediment systems are largely unknown. They point out work where the reflectance response of soil-water mixtures was found to be largely insensitive to concentrations above 75 to several hundred mg/l, depending upon the soil source. The lower limit appears controlled by data precision, since variability is reported to become large at low sediment concentrations. The use of gravimetric measurements of total solids to

indicate suspended solids could account for much of the variability, since the former will include dissolved solids as well.

They report that the best relationship for sediment concentration (treated as the dependent variable Y) to reflectance (treated as the independent variable X) is of the form

$$Y = X^n \quad (14)$$

Work was reviewed where values of n were reported to be equal to, greater than, and less than unity. If $n > 1$, the sediment concentration becomes increasingly more sensitive to incremental increases in reflectance. This implies range limits because the sediment concentration will respond so sensitively to reflectance that errors in its measurement must be small or the stability of the relationship is destroyed. If $n < 1$, the reverse is true, and the practical upper limit is set by the precision of the sediment measurements used to establish the relationship.

In their own work, they report on aircraft platform (6.1 km altitude) remotely sensed data obtained using 14 bands of a 24 channel MSS with a wavelength range of 375 to 13,000 nm. They found that in the ultraviolet range (<400 nm) and to 500 nm, reflectances were largely insensitive to suspended sediment. In the overall 500-740 nm range, differences were significant at the one percent level, with the 588-643 and 650-690 nm bands accounting for nearly half of the total reflectance. They note that, "the rapidly changing, yet parallel plots in the λ range encompassing both bands, suggest that reflectance is a specific and direct measurement of suspended sediment rather than an indirect measure of the changed spectral characteristics of the water caused by either the interference of sediment or a water-sediment interaction." These bands were found to have the least curvilinearity and greatest sensitivity over a 13 to 232 mg/l concentration range.

The plot for the 720-760 nm band was essentially a vertical line, and from 740 to 1300 nm there was virtually no response to sediment. It was noted that, in general, $n \geq 1$ and marked changes in sediment characteristics could alter preferred bands for measurement.

SECTION V
CONCLUSION AND RECOMMENDATION

From the brief review of recent experience with remote sensing of suspended sediment given in the preceding Section, it is apparent that some progress is being made from "pretty pictures" to quantified data products, but much of the journey remains ahead. Furthermore, the progress so far has not been without some internal conflict, which is understandable in view of the complexity of the problem. It does appear, however, that a more unified approach would accelerate the progress and help resolve seeming discrepancies in the results obtained by different workers in the area. Two ingredients essential to maximizing the probability of success, within a reasonable time frame and at an affordable cost, are a lead agency and an integrated, multidisciplinary program. The National Aeronautics and Space Administration, in cooperation with other agencies such as the U.S. Army Corps of Engineers, the U.S. Department of Agriculture, the U.S. Environmental Protection Agency, the U.S. Geological Survey, and the National Oceanographic and Atmospheric Agency, to name a few in the Federal sector, appears to be the logical choice to assume such a lead role, but that point will not be belabored here. Rather, although it is outside the scope of the present effort to define an integrated program, we do wish to consider a few elements that should be emphasized in it.

IMPORTANT PROGRAM CONSIDERATIONS

The brief review of some of the aspects of mechanics involved in sediment determination given in the preceding Sections provides some insight into considerations that must be taken into account in order to lay out a viable, integrated program. One of the chief concerns of developing the capability for the remote sensing of suspended

sediment concentrations in water is the truthfulness of ground truth data. These data will be used to construct and calibrate measurement techniques and for subsequent verification. Two aspects must be included in the program related to these direct measurements. First, the physical factors touched on in Section II and the lessons learned by the experience reviewed in Section IV suggest that the timing of the collection of ground truth data is of critical importance. For most locations, samples will have to be collected in as near a time coincidence with the remote sensor pass as possible, certainly on the same day. This has strong implications in the program design.

The second aspect related to direct measurement deals with the actual taking of the samples. Standardization of sampling equipment and techniques is mandatory if comparable results are to be obtained. The program should include the development of automated sampling equipment and use protocols in order to avoid data misinterpretation that could arise from factors such as those discussed in Section III. The importance of this aspect of the overall program cannot be overemphasized.

Although not a part of direct sediment measurement per se, the need for good ground registration accuracy was pointed out in Sections II and IV. The program should include consideration of this factor and, when warranted, development of baseline techniques for improvement of the ability to associate a ground truth site with the appropriate image area should be allowed for. The proper location and number of ground truth sites are also important considerations and will vary, not only with the local conditions of the area of interest, but with the intended purpose of the ground truth data. For example, many more sites would be required for system calibration than for system verification. The program must systematically address these factors as well.

Turning now to some of the aspects of indirect measurement, higher remote sensor platform altitudes are desirable to increase areal coverage and

provide data compaction. Atmospheric effects must be accounted for, however, and the program should include obtaining upwelling radiance measurements very near the surface coincidentally with the overpass of the higher altitude platform. Laboratory measurements of reflectance and transmittance of ground truth samples are also indicated as an integral part of the program. Work in this area may be facilitated by the use of standardized synthetic mixtures of predetermined characteristics, and the utility of such an endeavor should be investigated.

The analysis of much remotely sensed data is troubled by what can be essentially termed a high signal-to-noise ratio⁷ as was suggested by equation (12). There are many similarities between this signal processing problem and the one posed by underwater sound, as typified by the passive classification of a target by a modern SONAR system. One aspect of the program might well be devoted to a comparison of the respective signal processing requirements, with the aim of maximizing the utilization of signal processing technology already developed by the SONAR community.

Another major aspect of the program should deal with a realistic assessment of data costs. Although intuition suggests that remote sensing will be cost-effective in many situations, a cost-benefit study that addresses platform types, the quality of data products obtained, and the indirect cost aspects such as analysis costs, required personnel skill levels, etc., is necessary in order to allow trade-off studies to be from the overall estuarine and coastal zone management sense.

PROGRAM BENEFITS

The foregoing discussion of some of the aspects of an integrated, multidisciplinary program to reduce the quantitative remote measurement of suspended sediment to a routine practice within the state of the art emphasizes the need for a systems approach to the overall problem.

To illustrate the value of such a program, a few direct benefits to estuarine and coastal zone management will be mentioned. In all cases these benefits, presented in the form of data uses, are virtually unobtainable (at least in a practical sense) except by remote sensing technology. Such data uses include:

1. Hydrodynamic model generation and verification,
2. Monitoring land use effects,
3. Determination of outfall siting and effects,
4. Detection of dumping and effects,
5. Historical data base for predicting project impacts and trend development and forecasting,
6. Guide to minimize direct sampling requirements, and
7. Extrapolation of limited surface data over an entire water area.

These data uses, or program benefits, are a few of those suggested by Section I. Obviously, there would also be benefits, in a technology utilization sense, to areas other than the estuarine and coastal zone, since the fundamental technologies developed would be applicable to all surface waters.

RECOMMENDATION

It is recommended that a program plan be developed that would properly account for the complexities of the problem of indirect measurement of suspended sediment and, taking full advantage of pertinent prior work, would systematically set forth the research and development tasks that remain to be done in order to effect a timely and affordable solution to the problem.

The program plan should include state-of-the-art reviews of all involved disciplines and trade-off studies where alternative courses of action

are identified. It should also contain time-phased expenditure projections, critical milestones, and decision points. The development of such a plan is the first step in the unified approach to the problem, and is necessary in order to maximize the probability of success. Furthermore, the present time seems especially propitious for the development of such an integrated plan, since much duplication of effort and unnecessary work might be prevented, and the coordination so afforded could maximize the technological return on investment.

Lord Kelvin has provided a fitting closure to this treatise.

"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science.

William Thomson (1891-4)

SECTION VI

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